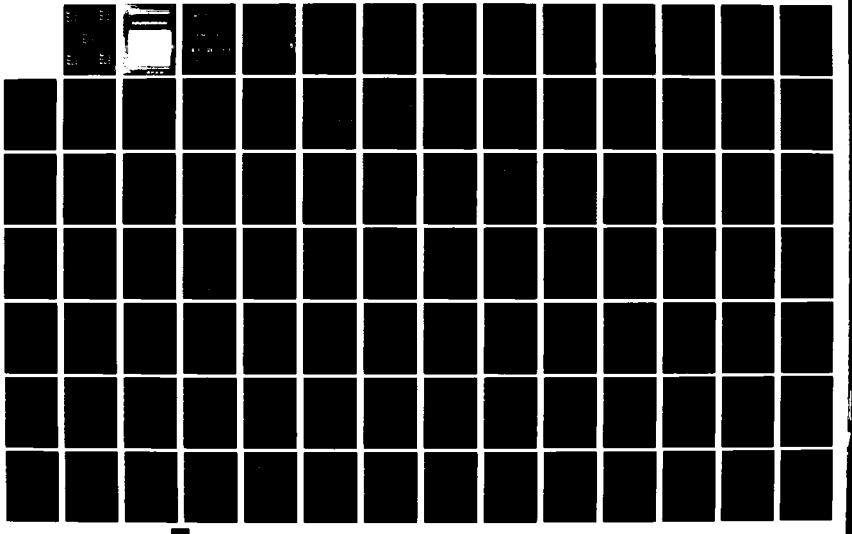
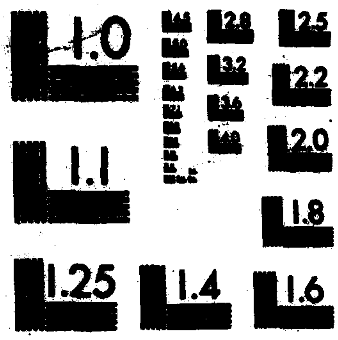
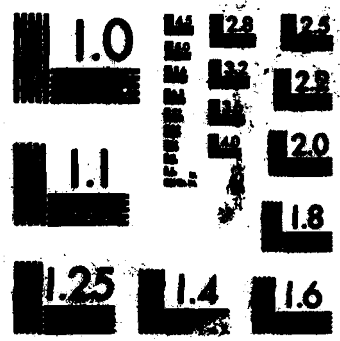
AD-A120 820 ANNUAL PROGRESS REPORT FOR JULY 1 1981 THROUGH JUNE 30 1/2
1982(U) ILLINOIS UNIV AT URBANA COORDINATED SCIENCE LAB
R T CHIEN ET AL. AUG 82 N00014-79-C-0424

UNCLASSIFIED F/G 5/2 NL

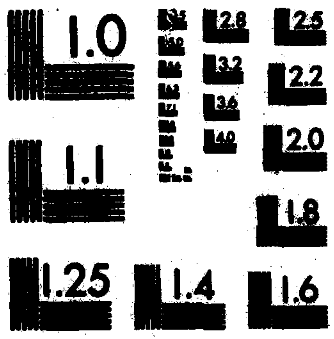




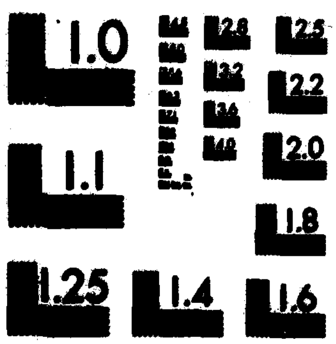
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



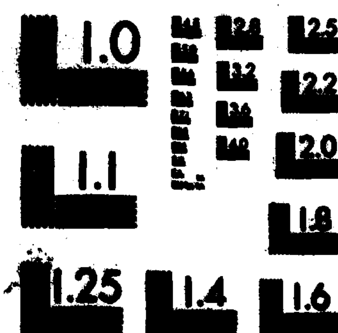
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



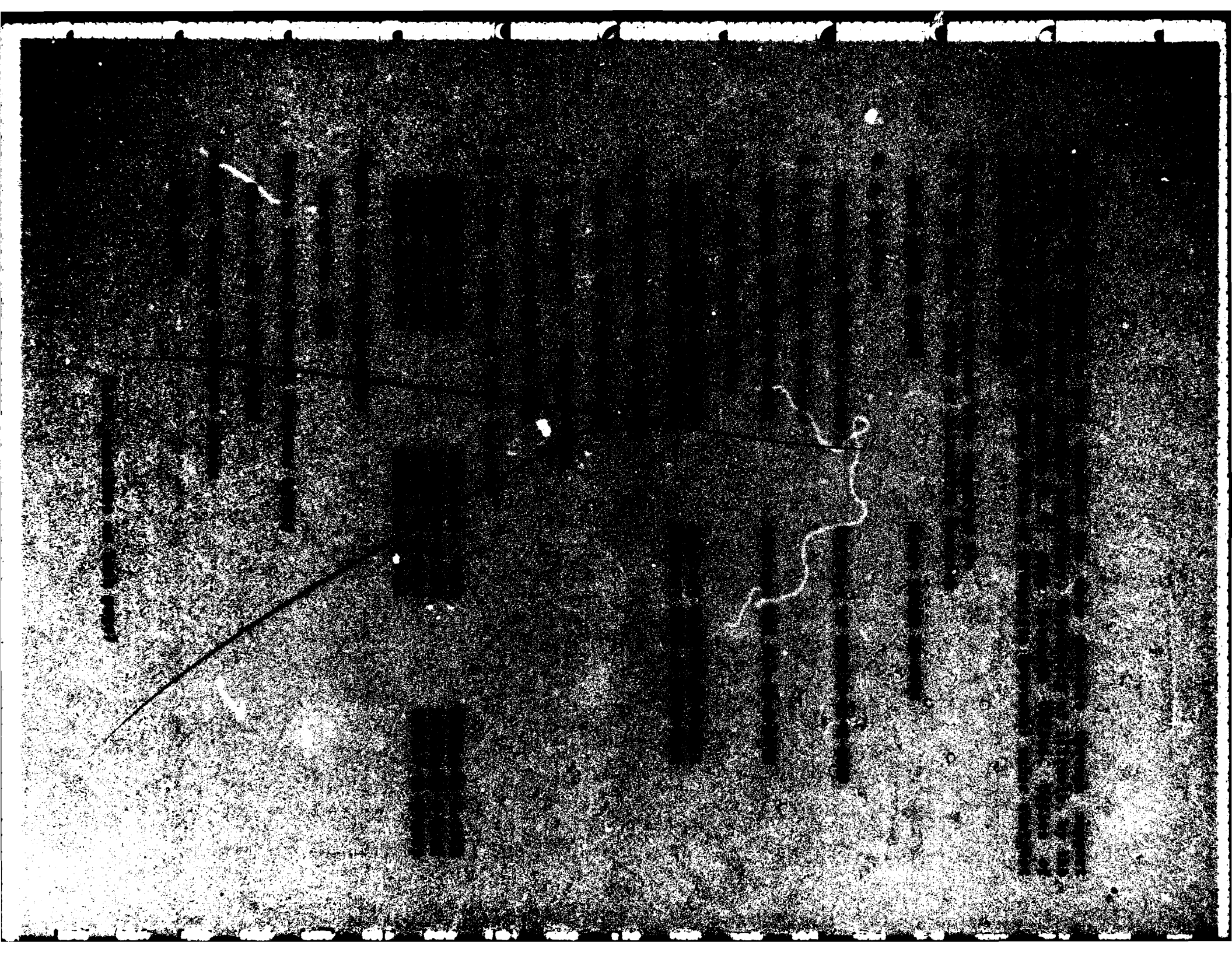
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A120820 / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANNUAL PROGRESS REPORT for July 1, 1981 through June 30, 1982	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s) N00014-79-C-0424
9. PERFORMING ORGANIZATION NAME AND ADDRESS Coordinated Science Laboratory University of Illinois at Urbana-Champaign Urbana, Illinois 61801	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Electronics Program through the Office of Naval Research, Arlington, VA 22217	12. REPORT DATE August, 1982
	13. NUMBER OF PAGES 179
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release. Distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes all sponsored research activities that occurred in the Coordinated Science Laboratory during the period July 1, 1981 to June 30, 1982. The summaries are categorized into nineteen technical areas. A comprehensive list of faculty, graduate students, publications, and supporting agencies during this period of time is included.

DD FORM 1 JAN 73 1473

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

COORDINATED SCIENCE LABORATORY

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ANNUAL PROGRESS REPORT 1981-82

August, 1982

Submitted by: R. T. Chien

Edited by: W. K. Jenkins

TABLE OF CONTENTS

COORDINATED SCIENCE LABORATORY PERSONNEL

Professor R. T. Chien, Director
Professor G. G. Judge, Associate Director
L. F. Selander, Assistant to the Director

Faculty

Abraham, J. A.
Ahuja, N.
Bajor, G.
Basar, T.
Bitzer, D. L.
Bowen, M.
Brown, D. J.
Brown, R. M.
Chien, R. T.
Cho, A. Y.
Coleman, P. D.
Cooper, D. H.
Cruz, J. B., Jr.
Davidson, E. S.
DeJong, G. F.
DeTemple, T. A.
Dow, J. D.
Eden, J. G.
Ehrlich, G.
El-Masry, E. I.
Flower, R. A.
Greene, J. E.
Haddad, A. H.
Hajek, B.
Hajj, I. N.
Handler, P.
Hayashi, Y.
Hess, K.
Huang, T. S.
Hunsinger, B. J.
Jackson, E. A.
Jenkins, W. K.
Johnson, W. B.
Judge, G. G.
Klein, M. V.
Kokotovic, P. V.
Leburton, J. P.
Lightner, M. R.
Looze, D. P.
Loui, M. C.
Mayeda, W.
McKliece, R. J.
Michie, D.
Mittra, R.
Morkoç, H.
Muller, D. E.
Munson, D. C., Jr.
Patel, J. H.
Perkins, W. R.
Poor, H. V.
Preparata, F. P.
Pursley, M. B.
Raether, M.
Rao, B. R.
Ray, S. R.
Rouse, W. B.
Sarwate, D. V.
Sauer, P. W.
Schlansker, M. S.
Slottow, H. G.
Smith, L.
Stillman, G. E.
Streetman, B. G.
Swamy, S.
Tantaratana, S.
Trick, T. N.
Tucker, J. R.
Van Valkenburg, M. E.
Verdeyen, J. T.
Waltz, D. L.
Wax, N.
Williams, M. E.
Yen, S. M.

Academic Staff

Basar, T. U.
Chambers, R. S.
Fink, H.-W.
Kielblock, K. J.
Lennon, L. W.
Maran, L.
Merlin, R.
Mills, C.
Mon, K. K.
North, M.
Preece, S. E.
Ravlin, H.
Robins, C. G.
Rouse, S. H.
Selander, L.
Szilléry, E.
Wada, N.
Welborn, M.

Graduate Students

Aazhang, B.
Abrams, S.
Alpay, U.
Altman, E.
Amir, R.
Andreatta, R.
Archer, D.
Arnold, D.
Attaie, N.
Ault, S.
Banerjee, P.
Banerjee, S.
Barnett, S.
Benhabib, J.
Bereznak, B.
Bhooshan, S.R
Bilardi, G.
Blumer, A.
Bogus, E.
Bolognesi, T.
Bose, P.
Bovik, A.
Brahme, D.
Brass, S.
Brennan, K.
Bridwell, N.
Brown, A.
Bulman, G.
Cansever, D.
Chamberlain, R.
Chan, S.
Chan, Y.
Chang, C.
Chen, D.
Chia, W.
Chillarege, R.
Chin, B.
Chin, M.
Constrini, G.
Cook, L.
Coulman, D.
Cross, S.
Darragh, J.
Davis, R.
DeGroat, J.
DeJule, R.
Desai, H.
Desai, M.
Dinitz, R.
Dorfman, M.
Drummond, T.
Ekenberg, U.
Embree, P.
Emma, P.
Enge, P.
Fan, H.
Fang, S.
Farr, E.
Farwell, D.
Fischer, R.
Fleddermann, C.
Fletcher, R.
Frederick, W.
Freudenberg, J.
Fu, T.
Fuchs, K.
Fung, L.
Gahutu, D.
Garber, F.
Gavrilovic, P.
Geraniotis, E.
Gibbons, J.
Gollakota, M.
Gorbatkin, S.
Gordon, J.
Graf, M.
Greenberg, K.
Haase, M.
Hall, D.
Halperin, D.
Hanes, L.
Hayner, D.
Higgins, W.
Ho, W.
Hocevar, D.
Hoff, W.
Hoskins, M.
Houghton, M.
Hsieh, C.
Hsu, P.
Huang, K.
Ioannou, P.
Jha, N.
Jones, J.
Jou, J.
Kahhaleh, B.
Kaplan, M.
Kappauf, W.
Kastner, R.
Keck, K.
Keever, M.
Keller, S.
Kim, M.
Kinsel, J.
Klem, J.
Klinger, R.
Koob, G.
Kopp, W.
Kramer, B.
Krogh, B.
Krone, S.
LaMar, D.
Laha, S.
Lam, C.
Lee, B.
Lee, C.
Lee, S.
Lehnert, J.
Lepkowski, T.
Lilja, D.
Lindner, D.
Lo, T.
Low, T.
Lubben, D.
Lyons, W.
Mak, G.
Martersteck, J.
Martin, E.
Martin, P.
Massa, F.
McCaffrey, C.
McEwen, R.
McNiven, G.
Mendoza, J.
Milito, R.
Miller, J.
Miller, R.
Nash, C.
Nayeri, M.
Needham, M.
Nguyen, N.
Norton, R.
O'Brien, J.
O'Rorke, P.
Oberstar, J.
Ogier, R.
Osmundson, J.
Pajerski, A.
Pan, Y.
Parent, P.
Paul, D.
Pavlik, T.
Payne, D.

Graduate Students

[illegible], L.
[illegible], G.
[illegible], G.
[illegible], A.
[illegible], J.
[illegible], R.
[illegible], J.
[illegible], M.
[illegible], J.
[illegible], E.
[illegible], V.
[illegible], H.
[illegible], A.
[illegible], L.
[illegible], V.
[illegible], A.
[illegible], L.
[illegible], L.
[illegible]
[illegible], T.
[illegible]
[illegible], G.
[illegible], A.

[illegible], H.
[illegible], A.
[illegible], G.
[illegible], R.
[illegible], A.
[illegible], S.
[illegible], R.
[illegible], G.
[illegible], D.
[illegible], C.
[illegible]
[illegible], J.
[illegible], J., Jr.
[illegible], S.
[illegible], R.
[illegible], T.
[illegible], R.
[illegible], G.
[illegible], G.
[illegible], L.
[illegible], G.
[illegible]
[illegible]
[illegible], G.

Trish, T.
Tsai, K.
Tacoryan, H.
Uffenheide, C.
Vastola, K.
Verdi, S.
Vittitow, J.
Wallace, N.
Wang, S.
Wang, T.
Watanabe, F.
Webb, K.
Wei, V.
Welcome, M.
Wen, J.
West, P.
Wilson, J.
Windhorn, T.
Wolf, R.
Wong, C.
Wrigley, J., Jr.
Yen, R.
Yu, A.
Yuan, C.

Nonacademic Staff

[illegible], H. H.
[illegible], T. L.
[illegible], V. D.
[illegible], C. A.
[illegible], S. A.
[illegible]
[illegible], C. A.
[illegible], L. E.
[illegible], F. L.
[illegible], G.
[illegible], H. R.
[illegible], H. L.
[illegible], G. R.

[illegible], E. T.
[illegible]
[illegible], C. L.
[illegible], C. A.
[illegible], R. E.
[illegible], A. L.
[illegible], W. I.
Little, G.
[illegible], C. R.
MacFarlane, R. F.
[illegible], F.
[illegible], E. P.
[illegible], V. J.

Murphy, D. L.
Ferrero, B. J.
Ray, H. L.
Roberts, G. L.
Rose, H. T.
Schuyler, J. L.
Suter, H. E.
Thrasher, V. A.
Vossos, N.
Vopong, R.
Williams, S. D.
Young, P. A.

1. MOLECULAR BEAM EPITAXY

Journal Articles

1.1 M. N. Afsar, K. J. Button, A. Y. Cho and H. Morkoc, "Ultimate method for unambiguous identification of all donors in epitaxial GaAs and related compounds," International J. of Infrared and Millimeter Waves, vol. 2, pp. 1113-1121, 1981.

1.2 H. Beneking, A. Y. Cho, J. J. M. Dekkers and H. Morkoc, "Buried channel MESFETs on MBE material: Scattering parameters and intermodulation signal distortion," IEEE Trans. on Electronic Devices, vol. ED-29, pp. 811-814, 1982.

1.3 K. Y. Cheng, A. Y. Cho, T. J. Drummond and H. Morkoc, "Electron mobilities in modulation doped $Ga_{0.47}In_{0.53}As/Al_{0.47}In_{0.52}As$ heterojunctions grown by molecular beam epitaxy," Applied Physics Letters, vol. 40, pp. 147-149, 1981.

1.4 P. D. Coleman, J. Freeman, H. Morkoc, K Hess, B. G. Streetman and M. Keever, "Demonstration of a new oscillator principle in heterojunctions," Applied Physics Letters, vol. 40, pp. 493-495, March 1982.

1.5 R. Dingle, C. Weisbuch, H. L. Stormer, H. Morkoc and A. Y. Cho, "Characterization of high purity GaAs grown by molecular beam epitaxy," Applied Physics Letters, vol. 40, pp. 507-510, 1982.

1.6 T. J. Drummond, R. Fischer, H. Morkoc and P. Miller, "Influence of substrate temperature on the mobility of modulation doped $Al_xGa_{1-x}As$/-GaAs heterojunctions grown by MBE," Applied Physics Letters, vol. 40, pp. 430-432, 1982.

1.7 T. J. Drummond, R. Fischer, P. Miller, H. Morkoc and A. Y Cho, "Influence of substrate temperature on electron mobility in normal and inverted single period modulation doped $Al_xGa_{1-x}As$/GaAs structures," J. Vacuum Science and Technology (to appear).

1.8 T. J. Drummond, M. Keever, W. Kopp, H. Morkoc, K. Hess, A. Y. Cho and B. G. Streetman, "Field dependence of mobility in $Al_{0.2}Ga_{0.8}As$/GaAs heterojunctions at very low fields," Electronics Letters, vol. 17, pp. 545-547, 1981.

1.9 T. J. Drummond, M. Keever and H. Morkoc, "Comparison of single and multiple period modulation doped $Al_xGa_{1-x}As$/GaAs heterostructures for FETs," Japanese J. of Applied Physics Letters, vol. 21, pp. L65-L67, 1982.

1.10 T. J. Drummond, W. Kopp, R. Fischer, H. Morkoc, R. E. Thorne and A. Y. Cho, "Photoconductivity effects in extremely high mobility modulation doped (Al,Ga)As/GaAs heterostructures," J. of Applied Physics, vol. 53, pp. 1238-1240, 1982.

1.11 T. J. Drummond, W. Kopp, R. Fischer and H. Morkoc, "Influence of AlAs mole fraction on the mobility of (Al,Ga)As/GaAs heterostructures," J. of Applied Physics, vol. 53, pp. 1028-1029, 1982.

1.12 T. J. Drummond, W. Kopp, M. Keever, H. Morkoc and A. Y. Cho, "Electron mobility in single and multiple period modulation doped (Al,Ga)As/GaAs heterostructures," J. of Applied Physics, vol. 53, pp. 1023-1027, 1982.

1.13 T. J. Drummond, W. Kopp and H. Morkoc, "Three period (Al,Ga)As/GaAs heterostructures with extremely high mobilities," Electronics Letters, vol. 17, pp. 442-444, 1981.

1.14 T. J. Drummond, W. Kopp, H. Morkoc, K. Hess, A. Y. Cho and B. G. Streetman, "Effect of background doping on the electron mobility of (Al,Ga)As/GaAs heterostructures," J. of Applied Physics, vol. 52, pp. 5689-5690, 1981.

1.15 T. J. Drummond, W. Kopp, H. Morkoc and M. Keever, "Transport in modulation doped structures ($Al_xGa_{1-x}As$/GaAs): Correlations with Monte Carlo calculations (GaAs)," Applied Physics Letters (to appear).

1.16 T. J. Drummond, W. Kopp, R. E. Thorne, R. Fischer and H. Morkoc, "Influence of $Al_xGa_{1-x}As$ buffer layers on the performance of modulation doped field effect transistors," Applied Physics Letters, vol. 40, pp. 879-881, 1982.

1.17 T. J. Drummond, W. G. Lyons, R. Fischer, R. E. Thorne, H. Morkoc, C. G. Hopkins and C. A. Evans, Jr., "Si incorporation in $Al_xGa_{1-x}As$ grown by molecular beam epitaxy," J. of Vacuum Science and Technology (to appear).

1.18 T. J. Drummond, H. Morkoç, K. Y. Cheng and A. Y. Cho, "Current transport in modulation doped $Ga_{0.47}In_{0.53}As/As_{0.48}In_{0.52}As$ heterojunctions at moderate fields," J. of Applied Physics, vol. 53, pp. 3654-3657, 1982.

1.19 T. J. Drummond, H. Morkoç, K. Hess and A. Y. Cho, "Experimental and theoretical electron mobility of modulation doped $Al_xGa_{1-x}As/GaAs$ heterostructures grown by molecular beam epitaxy," J. of Applied Physics, vol. 52, pp. 5231-5234, 1981.

1.20 T. J. Drummond, H. Morkoç and A. Y. Cho, "MBE growth of (Al,Ga)As/GaAs heterostructures," J. of Crystal Growth, vol. 56, pp. 449-454, 1982.

1.21 T. J. Drummond, H. Morkoç, S. L. Su, R. Fischer and A. Y. Cho, "Enhanced mobility in inverted $Al_xGa_{1-x}As/GaAs$ heterojunctions: Binary on top of ternary," Electronics Letters, vol. 17, pp. 870-871, 1981.

1.22 T. J. Drummond, T. Wang, W. Kopp, H. Morkoç, R. E. Thorne and S. L. Su, "A novel normally-off camel diode gate GaAs field effect transistor," Applied Physics Letters, vol. 40, pp. 834-836, 1982.

1.23 N. Holonyak, Jr., W. D. Laidig, M. Camras, H. Morkoç, T. J. Drummond and K. Hess, "Clustering and phonon effects in $Al_xGa_{1-x}As$-GaAs quantum well heterostructure lasers grown by molecular beam epitaxy," Solid State Communications, vol. 40, pp. 71-74, 1981.

1.24 N. Holonyak, Jr., W. Laidig, M. Camras, H. Morkoç, T. J. Drummond, K. Hess and M. S. Burroughs, "Clustering in MBE $Al_xGa_{1-x}As$-GaAs quantum well heterojunction lasers," J. of Applied Physics, vol. 52, pp. 7201-7202, 1981.

1.25 M. J. Hoskins, H. Morkoç and B. J. Hunsinger, "Charge transport by surface acoustic waves in GaAs," Applied Physics Letters (to appear).

1.26 M. Keever, T. J. Drummond, H. Morkoç, K. Hess and B. G. Streetman, "High field transport in GaAs-$Al_xGa_{1-x}As$ heterojunction layers," IEEE Trans. on Electron Devices, vol. ED-28, p. 1233, 1981.

1.27 M. Keever, W. Kopp, T. J. Drummond, H. Morkoç and K. Hess, "Current transport in modulation doped $Al_xGa_{1-x}As/GaAs$ heterojunction structures at moderate field strengths," Japanese J. of Applied Physics, vol. 21, Oct. 1982.

1.28 W. Kopp, T. J. Drummond, T. Wang, H. Morkoç and S. L. Su, "A novel camel diode gate GaAs FET," IEEE Electronic Device Letters, vol. EDL-3, pp. 86-88, 1982.

1.29 W. Kopp, R. Fischer, R. E. Thorne, S. L. Su, T. J. Drummond, H. Morkoç and A. Y. Cho, "A New $Al_{0.3}Ga_{0.7}As$/GaAs Modulation Doped FET," Electronic Device Letters, vol. EDL-3, pp. 109-111, 1982.

1.30 W. Kopp, H. Morkoç, T. J. Drummond and S. L. Su, "Characteristics of submicron gate GaAs FETs with $Al_{0.3}Ga_{0.7}As$ buffers: Effects of interface quality," IEEE Electronic Device Letters, vol. EDL-3, pp. 46-48, 1982.

1.31 W. Kopp, S. L. Su, R. Fischer, W. G. Lyons, R. E. Thorne, T. J. Drummond, H. Morkoç and A. Y. Cho, "Use of a GaAs smoothing layer to improve the heterointerface of GaAs/$Al_xGa_{1-x}As$ field effect transistors," Applied Physics Letters (to appear).

1.32 T. S. Low, G. E. Stillman, A. Y. Cho, H. Morkoç and A. R. Calawa, "Spectroscopy of donors in high purity MBE GaAs," Applied Physics Letters, vol. 40, pp. 611-613, 1982.

1.33 M. V. McLevidge, H. T. Yuan, W. M. Duncan, W. R. Frensley, F. H. Doerbeck, H. Morkoç and T. J. Drummond, "GaAs/AlGaAs heterojunction bipolar transistors for integrated circuit applications," IEEE Electronic Devices, vol. EDL-3, pp. 43-46, 1982.

1.34 H. Morkoç, "A short channel GaAs FET fabricated like a MESFET, but operating like a JFET," Electronics Letters, vol. 18, pp. 258-259, 1982.

1.35 H. Morkoç, "A short channel GaAs FET fabricated like a MESFET, but operating like a JFET," Japanese J. of Applied Physics Letters, vol. 21, pp. 233-234, 1982.

1.36 H. Morkoç, "Current transport in modulation doped (Al,Ga)As/GaAs heterostructures: Applications to high speed FETs," IEEE Electronic Device Letters, vol. EDL-2, pp. 260-261, 1981.

1.37 H. Morkoç, T. J. Drummond and R. Fischer, "Interfacial properties of (Al,Ga)As/GaAs structures: Effects of substrate temperature during growth by MBE," J. of Applied Physics, vol. 53, pp. 1030-1033, 1982.

1.38 H. Morkoç, T. J. Drummond, R Fischer and A. Y. Cho, "Moderate mobility enhancement in single period $Al_xGa_{1-x}As$/GaAs heterojunctions with GaAs on top," J. of Applied Physics, vol. 53, pp. 3321-3323, 1982.

1.39 H. Morkoç, T. J. Drummond, W. Kopp and R. Fischer, "Influence of substrate temperature on the morphology of $Al_xGa_{1-x}As$ grown by molecular beam epitaxy," J. of the Electrochemical Society, vol. 129, pp. 824-826, 1982.

1.40 H. Morkoç, T. J. Drummond and M. Omori, "GaAs MESFETs by molecular beam epitaxy," IEEE Trans. on Electronic Devices, vol. ED-29, pp. 222-225, 1982.

1.41 H. Morkoç, T. J. Drummond, R. E. Thorne and W. Kopp, "Mobility enhancement in inverted $Al_xGa_{1-x}As$/GaAs modulation doped structures and its dependence on donor-electron separation," Japanese J. of Applied Physics, vol. 20, no. 12, pp. L913-916, 1981.

1.42 H. Morkoç, W. Kopp, T. J. Drummond, S. L. Su and R. E. Thorne, "Submicron gate GaAs/$Al_{0.3}Ga_{0.7}As$ MESFETs with extremely sharp interfaces (40 Å)," IEEE Trans. on Electronic Devices, vol. ED-29, pp. 1013-1018, 1982.

1.43 H. Morkoç, R. Stamberg and E. Krikoran, "Whisker growth during epitaxy of GaAs by molecular beam epitaxy," Japanese J. of Applied Physics, vol. 21, pp. L230-L232, 1982.

1.44 M. Omori, T. J. Drummond and H. Morkoç, "Low noise GaAs field effect transistors prepared by molecular beam epitaxy," Applied Physics Letters, vol. 39, pp. 566-569, 1981.

1.45 A. Rockett, T. J. Drummond, J. E. Greene and H. Morkoç, "Surface segregation model for Sn in MBE grown GaAs," J. of Applied Physics (to appear).

1.46 S. L. Su, R. E. Thorne, R. Fischer, W. G. Lyons and H. Morkoç, "Influence of buffer thickness on the performance of GaAs field effect transistors prepared by molecular beam epitaxy," J. of Vacuum Science and Technology (to appear).

1.47 R. E. Thorne, T. J. Drummond, W. G. Lyons, R. Fischer and H. Morkoç, "An explanation for anomalous donor activation energies in $Al_{0.35}Ga_{0.65}As$," Applied Physics Letters, vol. 41, pp. 189-191, 1982.

1.48 R. E. Thorne, R. Fischer, S. L. Su, W. Kopp, T. J. Drummond and H. Morkoç, "Performance of inverted structure modulation doped Schottky barrier field effect transistors," Japanese J. of Applied Physics Letters, vol. 21, pp. L223-L224, 1982.

1.49 R. E. Thorne, S. L. Su, W. Kopp, R. Fischer, T. J. Drummond and H. Morkoç, "Normally-on and normally-off camel diode gate GaAs FETs for large scale integration," J. of Applied Physics (to appear).

Conference Papers

1.50 E. E. Mendez, G. Bastard, L. L. Chang, L. Esaki, H. Morkoc and R. Fischer, "Electric field-induced quenching of luminescence in quantum wells," Proc. of the 16th International Conf. on Physics of Semiconductors, Montpellier, France, 1982.

1.51 H. Morkoc, N. Holonyak, Jr., T. J. Drummond, M. D. Camras and R. Fischer, "$Al_xGa_{1-x}As/GaAs$ quantum well lasers grown by molecular beam epitaxy," Proc. of the Society of Photo-Optical Instrumentation-Engineers, 1982.

2. SEMICONDUCTOR MATERIALS AND DEVICES

Journal Articles

2.1 E. R. Anderson, B. A. Vojak, N. Holonyak, Jr., G. E. Stillman, J. J. Coleman, and P. D. Dapkus, "Transient and noise characteristics of quantum-well heterostructure lasers," Applied Physics Letters, vol. 38, pp. 585-587, 1981.

2.2 G. E. Bulman, L. W. Cook and G. E. Stillman, "The effects of electroabsorption on the determination of ionization coefficients," Applied Physics Letters, vol. 39, pp. 813-815, 1981.

2.3 L. W. Cook, G. E. Bulman and G. E. Stillman, "Electron and hole impact ionization coefficients in InP determined by photomultiplication measurements," Applied Physics Letters, vol. 40, pp. 589-591, 1982.

2.4 N. Tabatabaie, G. E. Stillman, R. Chin and P. D. Dapkus, "Tunneling in the reverse dark current of GaAlAsSb avalanche photodiodes," Applied Physics Letters, vol. 40, pp. 415-417, 1982.

2.5 M. M. Tashima, L. W. Cook and G. E. Stillman, "The application of x-ray diffraction measurements in the growth of LPE InGaAsP/InP," J. of Crystal Growth, vol. 54, pp. 132-137, 1981.

2.6 M. M. Tashima, L. W. Cook, N. Tabatabaie and G. E. Stillman, "The effect of lattice mismatch on hole diffusion lengths in liquid phase epitaxial InGaAsP (λ_g = 1.15 μm)/InP," Applied Physics Letters, vol. 38, pp. 1009-1011, 1981.

2.7 M. M. Tashima, L. W. Cook and G. E. Stillman, "Room-temperature electron diffusion lengths in liquid phase epitaxial InGaAsP and InGaAs," Applied Physics Letters, vol. 39, pp. 960-961, 1981

2.8 M. M. Tashima, L. W. Cook and G. E. Stillman, "Minority carrier diffusion lengths in liquid phase epitaxial InGaAsP and InGaAs," J. of Electronic Materials, vol. 11, 831-846, 1982.

Conference Papers

2.9 L. W. Cook, N. Tabatabaie, M. M. Tashima, T. H. Windhorn, G. E. Bulman and G. E. Stillman, "Low leakage LPE-grown InGaAs/InP avalanche photodiodes," Proc. of the International Symposium on GaAs and Related Compounds, Vienna, 1980, (Institute of Physics, London and Bristol, 1981, Conf. Series No. 56, Chapter 6) pp. 361-370, 1981.

2.10 G. E. Stillman, L. W. Cook, M. M. Tashima and N. Tabatabaie, "InGaAs avalanche photodetectors," Proc. of the SPIE Technical Symposium, Los Angeles, vol. 272, pp. 2-10, 1981.

2.11 G. E. Stillman, L. W. Cook, T. J. Roth and M. M. Tashima, "Compound semiconductor materials for near-infrared photodetectors," Proc. of the SPIE Technical Symposium, Washington, D. C., vol. 285, pp. 66-73, 1981.

2.12 L. M. Zinkiewicz, T. J. Roth, B. J. Skromme and G. E. Stillman, "The vapor phase growth of InP and $In_xGa_{1-x}As$ by the hydride ($In-Ga-AsH_3-HClH_2$) technique," Proc. of the International Symposium of GaAs and Related Compounds, Vienna, 1980 (Institute of Physics, London and Bristol, Conf. Series No. 56, Chapter 6) pp. 19-28, 1981.

2.13 L. W. Cook, G. E. Bulman, and G. E. Stillman, "Ionization coefficient determination in InP by analysis of avalanche photomultiplication and noise measurements," Proc. of the International Symposium on GaAs and Related Compounds, Oiso, 1981 (Institute of Physics, London and Bristol, Conf. Series No. 63) pp. 281-282, 1982.

3. QUANTUM ELECTRONICS

Journal Articles

3.1 R. W. Andreatta, C. C. Abele, J. F. Osmundsen, J. G. Eden, D. Lubben and J. E. Greene, "Low temperature growth of polycrystalline Si and Ge films by ultraviolet laser photodissociation of silane and germane," Applied Physics Letters, vol. 40, pp. 183-185, Jan. 1982.

3.2 R. W. Andreatta, D. Lubben, J. G. Eden and J. E. Greene, "Growth of Si and Ge thin films by laser-induced chemical vapor deposition," J. of Vacuum Science and Technology, vol. 20, pp. 740-741, March 1982.

3.3 N. Ianno, J. T. Verdeyen, S. S. Chan and B. G. Streetman, "Plasma annealing of ion implanted semiconductors," Applied Physics Letters, vol. 39, no. 8, p. 622, 1981.

3.4 J. R. Tucker, J. H. Miller, Jr., K. Seeger and John Bardeen, "Tunneling theory of ac-induced dc conductivity for charge-density waves in $NbSe_3$," Physical Review B, vol. 25, no. 4, p. 2979, 1982.

Conference Paper

3.5 C. B. Fleddermann, J. T. Verdeyen and B. G. Streetman, "Discharge annealing of ion implanted silicon," Proc. of Laser and Electron-Beam Interactions with Solids Symposium of the Materials Research Society, ed. B. R. Appleton and G. K. Celler (Elsevier North-Holland) p. 795, 1982.

4. SEMICONDUCTOR PHYSICS

Book Chapter

4.1 D. K. Ferry, K. Hess and P. Vogl, "Physics and modeling of submicron insulated-gate field-effect transistors. II. Transport in the quantized inversion layer," in Microstructure Science and Technology/VLSI, Norman Einspruch (ed.), Academic Press, 1981.

4.2 K. Hess, "Aspects of High Field Transport in Semiconductor Heterolayers and Semiconductor Devices," in Advances in Electronics and Electron Physics, Cohen (ed.), Academic Press, in press.

Journal Articles

4.3 A. Bhattacharyya, B. G. Streetman and K. Hess, "Comments on the plasma annealing model to explain the dynamics of pulsed laser annealing of ion-implanted silicon," J. of Applied Physics, vol. 53, no. 2, Feb. 1982.

4.4 Anjan Bhattacharyya, V. Iyer, B. G. Streetman, J. E. Baker and P. Williams, "Electrical activation and impurity redistribution during pulsed laser annealing of BF^+_2 implanted amorphized silicon," IEEE Trans. on Components, Hybrids, and Manufacturing Technology, vol. CHMT-4, pp. 425-428, Dec. 1981.

4.5 Anjan Bhattacharyya and B. G. Streetman, "Dynamics of pulsed CO_2 laser annealing of silicon," J. Physics D: Applied Physics, vol. 14, pp. L67-L72, 1981.

4.6 A. Bhattacharyya, K. Hess and B. G. Streetman, "Comments on the plasma annealing model to explain the dynamics of pulsed laser annealing of ion-implanted silicon," J. of Applied Physics, vol. 53, p. 1261, Feb. 1982.

4.7 T. J. Drummond, M. Keever, W. Kopp, H. Morkoc, K. Hess, A. Y. Cho and B. G. Streetman, "Field dependence of mobility in $Al_{0.2}Ga_{0.8}As/GaAs$ heterojunctions at very low fields," Electronics Letters, vol. 17, pp. 545-547, 1981.

4.8 K. Hess, "Ballistic electron transport in semiconductors," IEEE Trans. on Electron Devices, vol. ED-28, 937, 1981.

4.9 K. Hess and J. D. Dow, "Deformation potentials of bulk semiconductors," Solid State Communications, vol. 40, pp. 371-373, 1981.

4.10 K. Hess, "Lateral transport in superlattices," Journal de Physiq, Oct. 1981.

4.11 N. J. Ianno, J. T. Verdeyen, S. S. Chan and B. G. Streetman, "Plasma annealing of ion implanted semiconductors," Applied Physics Letters, vol. 39, pp. 622-624, Oct. 1981.

4.12 H. Kafka and K. Hess, "A carrier temperature model simulation of a double-drift IMPATT diode," IEEE Trans. on Electron Devices, vol. ED-28, p. 831, 1981.

4.13 M. Keever, T. J. Drummond, H. Morkoç, M. Ludowise, K. Hess and B. G. Streetman, "Hall effect and mobility in heterojunction layers," J. of Applied Physics, vol. 53, pp. 1034-1036, 1982.

4.14 P. A. Martin, B. G. Streetman and K. Hess, "Electric field enhanced emission from non-coulombic traps in semiconductors," J. of Applied Physics, vol. 52, pp. 7409-7415, Dec. 1981.

4.15 K. K. Mon and K. Hess, "Resonance impact ionization in superlattices," Solid State Electronics (to appear).

4.16 K. K. Mon, K. Hess and John D. Dow, "Deformation potentials of superlattices and interfaces," J. of Vacuum Science and Technology, vol. 19, pp. 564-566, 1981.

4.17 J. D. Oberstar, H. Shichijo, M. Keever, B. G. Streetman, J. E. Baker and P. Williams, "Theoretical and empirical distributions for ion implantation profiles in InP," Radiation Effects, vol. 61, pp. 109-116, April 1982.

4.18 J. D. Oberstar and B. G. Streetman, "Annealing encapsulants for InP: II. Photoluminescence studies," Thin Solid Films (to appear).

4.19 J. D. Oberstar and B. G. Streetman, "Photoluminescence studies of surface damage states in InP," Surface Science, vol. 108, pp. L470-L476, July 1981.

4.20 J. D. Oberstar and B. G. Streetman, "Photoluminescence studies of ^{4}He and ^{9}Be implanted semi-insulating InP," J. of Applied Physics, vol. 53, July, 1982 (to appear).

4.21 J. D. Oberstar, B. G. Streetman, J. E. Baker, N. L. Finnegan, E. A. Sammann and P. Williams, "Annealing encapsulants for InP: I. Auger electron and secondary ion mass spectroscopic studies," Thin Solid Films (to appear).

4.22 J. D. Oberstar, B. G. Streetman, J. E. Baker and P. Williams, "SIMS studies of ^{9}Be implants in semi-insulating InP," J. of the Electrochemical Society, vol. 129, pp. 1312-1320, June 1982.

4.23 J. D. Oberstar, B. G. Streetman, J. E. Baker and P. Williams, "SIMS studies of semi-insulating InP amorphized by Mg and Si," J. of the Electrochemical Society, vol. 129, pp. 1320-1325, June 1982.

4.24 J. D. Oberstar, B. G. Streetman, J. E. Baker and P. Williams, "Iron and chromium redistribution in semi-insulating InP," J. of the Electrochemical Society, vol. 128, pp. 1814-1817, Aug. 1981.

4.25 J. D. Oberstar, B. G. Streetman, J. E. Baker, P. Williams, R. L. Henry and E. M. Swiggard, "Boron contamination and precipitation during the growth of InP," J. of Crystal Growth, vol 54, pp. 443-448, Sept. 1981.

4.26 J. D. Oberstar, B. G. Streetman and E. A. Sammann, "Cracking of SiO_2 layers on annealed InP," Thin Solid Films, vol. 81, pp. 347-356, 1981.

4.27 J. Y. Tang and K. Hess, "Investigation of transient electronic transport in GaAs following high energy injection," IEEE Trans. on Electron Devices (to appear).

4.28 J. Y. Tang, K. Hess, N. Holonyak, Jr., J. J. Coleman and P. D. Daphus, "The dynamics of electron-hole collection in quantum well heterostructures," J. of Applied Physics (to appear).

Conference Papers

4.29 C. Fleddermann, N. Ianno, J. T. Verdeyen and B. G. Streetman, "Discharge annealing of ion implanted silicon," MRS Symposium on Laser and Electron Beam Solid Interactions and Materials Processing, to be published, 1982.

4.30 J. Y. Tang, H. Shichijo, K. Hess and G. Iafrate, "Band-structure dependent impact ionization in silicon and gallium arsenide," Proc. of the 3rd International Conf. on Hot Electrons in Semiconductors, Montpellier, France, 1981.

5. THIN FILM PHYSICS

Journal Articles

5.1 R.W. Andreatta, C.C. Abele, J.F. Osmundsen, J.G. Eden, D. Lubben, and J.E. Greene, "Low temperature growth of polycrystalline Si and Ge films by UV-laser photodissociation of silane and germane," Applied Physics Lett., vol. 40, p. 183, 1982.

5.2 G. Bajor, K.C. Cadien, M.A. Ray, J.E. Greene, and P.S. Vijayakumar, "The growth of high quality Ge films on (100) Si by sputter deposition," Applied Physics Lett., vol. 40, p. 696, 1982.

5.3 J.E. Greene, "Epitaxial crystal growth by sputter deposition: Applications to semiconductors," Critical Reviews of Solid State Physics and Materials Science, (to appear).

5.4 J.E. Greene and S.A. Barnett, "Ion-surface interactions during vapor phase crystal growth by sputtering, MBE, and plasma enhanced CVD: Applications to semiconductors," J. Vac. Sci. Technol., (to appear).

5.5 J.E. Greene, S.A. Barnett, K.C. Cadien, and M.A. Ray, "Growth of single crystal GaAs and metastable $(GaSb)_{1-x}Ge_x$ alloys by sputter deposition: Ion-surface interaction effects," J. Crystal Growth, vol. 56, p 389, 1982.

5.6 J.E. Greene, K.C. Cadien, D. Lubben, G.A. Hawkins, G.R. Ericson, and J.R. Clarke, "Epitaxial Ge/GaAs heterostructures by scanned CW laser annealing of a-Ge layers on GaAs", Applied Physics Lett., vol. 39, p. 232, 1981.

5.7 J.E. Greene and A.H. Eltoukhy, "Semiconductor crystal growth by sputter deposition: A review," Surface and Interface Sciences, vol. 3, p. 34, 1981.

5.8 R.E. Klinger and J.E. Greene, "Reactive ion etching of GaAs in CCl_2F_2," Appl. Phys. Lett., vol. 38, p. 620, 1981.

5.9 A. Pan and J.E. Greene, "Interfacial chemistry effects on the adhesion of sputter deposited TiC films to steel substrates," Thin Solid Films (to appear).

5.10 A. Rockett, T.J. Drummond, J.E. Greene, and H. Morkoc, "Surface segregation model for Sn in MBE-grown GaAS", J. Appl. Phys. (to appear)

5.11 L.C. Witkowski, T.J. Drummond, S.A. Barnett, H. Morkoc, A.Y. Cho, and J.E. Greene, "Properties of high mobility $GaAs/Ga_{1-x}Al_xAs$ single period modulation doped heterojunctions," Electronics Lett., vol. 17, p. 126, 1981.

Conference Papers

5.12 R.W. Andreatta, J.G. Eden, D. Lubben, and J.E. Greene, Invited Paper: "Deposition of thin amorphous Si and Ge films by the ultraviolet photodissociation of silane of germane," Workshop on the Interaction of Laser Radiation with Surface for Application to Microelectronics, MIT, Cambridge Mass, May 1981.

5.13 R.W. Andreatta, D. Lubben, J.G. Eden, and J.E. Greene, "Growth of Si and Ge thin films by laser-induced chemical vapor deposition," 28th Annual American Vacuum Soc. Meeting , Anaheim, CA, October 1981.

5.14 K.C. Cadien, A.H. Eltoukhy, and J.E. Greene, "Growth of novel materials by glow discharge sputtering: Single crystal metastable $(GaSb)_{1-x}Ge_x$ alloys," 5th Intl. Symposium on Plasma Chemistry, Edinburgh, Scotland, August 1981

5.15 K.C. Cadien, M.A. Ray, S.M. Shin, J.M. Rigsee, S.A. Barnett, and J.E. Greene, "Ion mixing during film deposition: Growth of metastable semiconducting and metallic alloys," 28th Annual American Vacuum Soc. Meeting, Anaheim, CA, October 1981.

5.16 K.C. Cadien, M.A. Ray, S.M. Shin, J.M. Rigsbee, S.A. Barnett, and J.E. Greene, "Ion mixing effects during film deposition: Growth of semiconducting and metallic alloys," Materials Research Society Meeting, Boston, MA, November 1981.

5.17 J.E. Greene, Invited Paper: "Low energy ion bombardment enhanced effects during crystal growth from the vapor phase," 3rd Brazilian Microelectronics Conf., University of Campinas, Campinas, Brazil, July 1981.

5.18 J.E. Greene, Invited Paper: "Reactive ion etching of GaAs," 3rd Brazilian Microelectronics Conference, Univ. of Campinas, Campinas, Brazil, July 1981.

5.19 J.E. Greene, Invited Paper: "Film growth from the vapor phase," The Chemistry and Physics of Thin Films: Device and Coating Technology, Univ. of Illinois at Chicago Circle, Chicago, IL September 1981.

5.20 J.E. Greene, Invited Paper: "Non-equilibrium growth of new single crystal metastable semiconducting alloys", Physics and Chemistry of Semiconductor Interfaces, Pacific Grove, CA, 1982.

5.21 J.E. Greene, K.C. Cadien, D. Lubben, G.A. Hawkins, G.R. Ericson, and J.R. Clark, "Epitaxial Ge/GaAs heterostructures by scanned CW laser annealing of a-Ge layers on GaAs," Materials Research Society Meeting, Boston, MA, November 1981.

5.22 M.C. Gwinder, P.N. Uppal, L.C. Burton, L. Rivaud, and J.E. Greene, Invited Paper: "Composition analysis of heterojunctions by means of electron and optical spectroscopies," SPIE 24th Annual Symposium, San Diego, CA, August 1980.

5.23 R.H. Klinger and J.E. Greene, Invited Paper: "Reactive ion etching of GaAs", Texas 7th Annual Plasma Seminar, Palo Alto, CA, April 1981.

5.24 R.H. Klinger and J.E. Greene, Invited paper: "Reactive ion etching of GaAs in CCl_4, CCl_2F_2, and CF_4-based discharges," Dry Process Symposium, Tokyo, Japan, October 1981.

5.25 R.H. Klinger and J.E. Greene, "Reactive ion etching of GaAs in CCl_4, CCl_2F_2, and CF_4-based discharges," 5th Intl. Symposium on Plasma Chemistry, Edinburgh, Scotland, August 1981.

5.26 J.F. Osmundsen, C.C. Abele, J.G. Eden, D. Lubben, and J.E. Greene: Invited Paper: "CO_2 laser assisted photolytic growth of polycrystalline Ge and Si films," 12th Annual Thermal Electronic Workshop, Urbana, IL (April 1982).

6. MICROWAVE ACOUSTICS

Journal Articles

6.1 S. Datta, H. J. Hoskins, R. Adler and B. J. Hunsinger, "Mode conversion using a modified multistrip coupler," IEEE Trans. on Sonics and Ultrasonics, vol. SU-28, no. 6, pp. 468-4770, Nov. 1981.

6.2 H. J. Hoskins and B. J. Hunsinger, "Charge transport by surface acoustic waves in GaAs," Applied Physics Letters, Aug. 1982 (to appear).

Conference Papers

6.3 R. Miller and B. J. Hunsinger, "A comparison of feeding techniques for group-type unidirectional transducers," 4th Publication, IEEE Ultrasonics Symposium, pp. 1-6, 1981.

7. SURFACE STUDIES

Journal Articles

7.1 G. Ehrlich, "Diffusion in surface layers," CRC Critical Reviews of Solid State and Material Science, vol. 10, pp. 391-409, 1982.

7.2 H.-W. Fink and G. Ehrlich, "Direct observation of overlayer structures on W(110)," Surface Science, vol. 110, pp. L611-L614, 1981.

Conference Papers

7.3 G. Ehrlich and K. Stolt, "Quantitative studies of individual atoms and clusters on solids," 39th Annual Proc. of the Electron Microscopy Society of America, G. W. Bailey (ed.), Claitor's Publishing Div., Baton Rouge, pp. 2-5, 1981.

7.4 G. Ehrlich, "Direct observation of atoms on metals," Kendall Award Lecture, American Chemical Society, Las Vegas, March 1982 (abstract).

7.5 G. Ehrlich, "Diffusion on metals - A view on the atomic level," Conference on Atomic Diffusion on Amorphous and Crystalline Surfaces, Rutgers University, April 1982 (abstract).

7.6 H.-W. Fink and G. Ehrlich, "Overlayer growth and atomic interactions on W(110)," 4th European Conf. on Surface Science, University of Munster, W. Germany, Sept. 1981 (abstract).

7.7 H.-W. Fink and G. Ehrlich, "Binding energy of individual atoms to epitaxial surface layers," Physical Electronics Conf., Atlanta, June 1982 (abstract).

Technical Reports

7.8 S. G. Brass, "Dissociative chemisorption of methane on transition metals," CSL Repot R-939, Feb. 1982, UILU-ENG 82-2205.

7.9 B. H. Chin, "Formation of silicon nitride structures by direct electron-beam writing," CSL Report R-940, Feb. 1982, UILU-ENG 82-2206.

8. ELECTROMAGNETIC COMMUNICATION, RADIATION AND SCATTERING

Journal Articles

8.1 S. Kobayashi, R. Lampe, R. Mittra, and S. Ray, "Dielectric rod leaky-wave antennas for millimeter-wave applications," IEEE Trans. on Antennas and Propagation, vol. AP-29, no.5, pp. 822-824, Sept. 1981.

8.2 S. Kobayasi, R. Mittra, and R. Lampe, "Dielectric tapered rod antennas for millimeter-wave applications," IEEE Trans. on Antennas and Propagation, vol. AP-30 no. 1, pp. 44-53, Jan. 1982.

8.3 R. Mittra and R. Kastner, "A spectral domain approach for computing the radiation characteristics of a leaky-wave antenna for millimeter waves," IEEE Trans. on Antennas and Propagation, vol. AP-29 no. 4, pp. 652-654, July 1981.

8.4 T. R. Trinh and R. Mittra, "Coupling characteristics of planar dielectric waveguides of rectangular cross-section," IEEE Trans. on Microwave Theory and Techniques, vol. MIT-29 no. 9, pp. 875-880, Sept. 1981.

8.5 T. Trinh, R. Mittra, and R. Paleta, "Horn image-guide leaky-wave antenna," IEEE Trans. on Microwave Theory and Techniques, vol. MIT-29 no. 12, pp. 1310-1314, Dec. 1981.

8.6 T. Trinh and R. Mittra, "Field profile in a single-mode curved dielectric waveguide of rectangular cross section," IEEE Trans. on Microwave Theory and Techniques, vol. MIT-29 no. 12, pp. 1315-1318, Dec. 1981.

Conference Papers

8.7 N. Deo and R. Mittra, "Millimeter wave integrated circuits and systems," Allerton Antenna Symposium, Monticello, IL., Sept. 23-25, 1981.

8.8 R. Kastner and R. Mittra, "Numerically rigorous inverse scattering using stacked 2-D spectral-iterative approach," IEEE AP-S and URSI Symposium, Albuquerque, NM, May 24-28, 1982.

8.9 R. Kastner and R. Mittra, "A comparative study of the stacked 2-D spectral iterative technique, the moment method, asymptotic techniques and theBojarski's 3-D-K-space method," IEEE AP-S and URSI Symposium, Albuquerque, NM., May 24-28, 1982.

8.10 R. Kastner and R. Mittra, "Application of the stacked 2-D spectral-iteration technique (SIT) to perfectly conducting cylinders with H-mode excitation and to dielectric cylinders," IEEEAP-S and URSI Symposium, Albuquerque, NM., May 24-28, 1982.

8.11 S. Ray, R. Mittra, T. Trinh, and R. Paleta, "Recent developments in millimeter-wave antennas," Allerton Antenna Symposium, Monticello, IL., Sept. 23-25, 1981.

8.12 S. Ray and R. Mittra, "Spectral-iterative analysis of dielectric rod antennas," IEEE AP-S and URSI Symposium, Albuquerque, NM, May 24-28, 1982.

Technical Reports

8.13 A. Ciarkowski and R. Mittra, "Plane-wave diffraction by a wedge--A spectral domain approach," EM Lab Report 81-9, Nov. 1981.

8.14 R. Kastner and R. Mittra, "Spectral-domain iterative techniques for analyzing electromagnetic scattering from arbitrary bodies," EM Lab Report 82-1, June 1982.

9. PLASMA PHYSICS

9.1 S. Ault, R. Raether, and S. Sobhanian, "Response of the electric field in a positive column in helium to a current perturbation," J. of Applied Physics, vol. 52, no. 9, p. 5483, 1981.

10. RAREFIED GAS DYNAMICS AND COMPUTATIONAL GAS DYNAMICS

Journal Articles

10.1 S. M. Yen and F. G. Tcheremissine, "Monte Carlo solution of the nonlinear Boltzmann equation," Rarefied Gas Dynamics, Progress in Astronautics and Aeronautics, vol. 74, pp. 287-304, 1981.

10.2 S. M. Yen, "Numerical solution of the Boltzmann and Krook equations for a condensation problem," Rarefied Gas Dynamics, Progress in Astronautics and Aeronautics, vol. 74, pp. 356-362, 1981.

10.3 S. M. Yen and T. Ytrehus, "Treatment of the nonequilibrium vapor motion near an evaporating interphase boundary," Chemical Engineering Communications, vol. 10, pp. 357-367, 1981.

10.4 W. P. Walters and S. M. Yen, "Mean free path of emitted gas from spacecraft," J. of Vacuum Science Technology, vol. 20, no. 2, p. 255, Feb. 1982.

Conference Papers

10.5 D. R. Hall and S. M. Yen, "Implementation of nonreflective boundary condition at the outflow boundary," Proc. of Conf. on Numerical Implementation of Boundary Conditions, Ames, CA, p. 45, Oct. 1981.

10.6 S. M. Yen and S. H. Lee, "Numerical solution of the Euler equation for a compressible flow problem," 8th International Conf. on Numerical Methods in Fluid Dynamics, Aachen, Germany, June 1982 (to be published).

11. COMPUTER SYSTEMS

Journal Articles

11.1 J. A. Abraham and D. D. Gajski, "Design of testable structures described by simple loops," IEEE Trans. on Computers, vol. C-30, pp. 875-884, Nov. 1981.

11.2 T. C. K. Chou and J. A. Abraham, "Load balancing in distributed systems," IEEE Trans. on Software Engineering, vol. SE-8, pp. 401-412, July 1982.

11.3 J. H. Patel, "Performance of processor-memory interconnections for multiprocessors," IEEE Trans. on Computers, vol. C-30, pp. 771-780, Oct. 1981.

11.4 J. H. Patel, "Analysis of multiprocessors with private cache memories," IEEE Trans. on Computers, vol. C-31, pp. 296-304, April 1982.

11.5 J. H. Patel and L. Y. Fung, "Concurrent error detection in ALUs by recomputing with shifted operands," IEEE Trans. on Computers, vol. C-31, pp. 589-595, July 1982.

11.6 D. W-L. Yen, J. H. Patel and E. S. Davidson, "Memory interference in synchronous multiprocessor systems," IEEE Trans. on Computers, vol. C-31, Nov. 1982 (to appear).

11.7 P. C-C. Yeh, J. H. Patel and E. S. Davidson, "Shared cache for multiple-stream computer systems," IEEE Trans. on Computers, vol. C-31, Dec. 1982 (to appear).

Conference Papers

11.8 J. A. Abraham, "Functional level test generation for complex digital systems," (Invited position paper), Digest 1981 International Test Conf., Philadelphia, Pennsylvania, pp. 461-462, Oct. 1981.

11.9 R. M. Apte, N.-S. Chang and J. A. Abraham, "Logic function extraction for NMOS circuits," Proc. 1982 International Conf. on Circuits and Computers, New York, Sept. 1982 (to appear).

11.10 P. Banerjee and J. A. Abraham, "Fault Characterization of MOS VLSI circuits," Proc. 1982 International Conf. on Circuits and Computers, New York, Sept. 1982 (to appear).

11.11 P. Bose and J. A. Abraham, "Test generation for programmable logic arrays," Proc. 19th Design Automation Conf., Las Vegas, pp. 574-580, June 1982.

11.12 G. F. Grohoski and J. H. Patel, "A performance model for instruction prefetch in pipelined instruction units," Proc. 1982 International Conf. on Parallel Processing, pp. 248-252, Aug. 1982.

11.13 K. Huang and J. A. Abraham, "Low cost schemes for fault tolerance in matrix operations with array processors," Proc. 12th International Symposium on Fault-Tolerant Computing, Santa Monica, California, pp. 330-337, June 1982.

11.14 K. Huang and J. A. Abraham, "Efficient parallel algorithms for processor arrays," Proc. 1982 International Conf. on Parallel Processing, Bellaire, Michigan, pp. 271-279, Aug. 1982.

11.15 A. J. Kessler and J. H. Patel, "Reconfigurable parallel pipelines for fault tolerance," Proc. 1982 International Conf. on Circuits and Computers, Sept. 1982 (to appear).

11.16 G.-P. Mak, J. A. Abraham and E. S. Davidson, "The design of PLAs with concurrent error detection," Proc. 12th International Symposium on Fault-Tolerant Computing, Santa Monica, California, pp. 303-310, June 1982.

11.17 R. L. Norton and J. A. Abraham, "Using write back cache to improve performance of multiuser multiprocessors," Proc. 1982 International Conf. on Parallel Processing, Bellaire, Michigan, pp. 326-331, Aug. 1982.

11.18 J. H. Patel, "A performance model for multiprocessors with private cache memories," Proc. 1981 International Conf. on Parallel Processing, pp. 314-317, Aug. 1981.

11.19 J. H. Patel and L. Y. Fung, "Multiplier and divider arrays with concurrent error detection," Proc. 1982 International Symposium on Fault-Tolerant Computing, pp. 325-329, June 1982.

11.20 J. H. Patel, "Application of time-redundancy to fault-tolerance," Proc. 1982 National Electronics Conf., Oct. 1982 (to appear).

11.21 A. R. Pleszkun, B. R. Rau, and E. S. Davidson, "An address prediction mechanism for reducing processor-memory address bandwidth," IEEE Computer Society Workshop on Computer Architecture for Pattern Analysis and Image Database Management, pp. 141-148, Nov. 1981.

12. APPLIED COMPUTATION THEORY

Journal Articles

12.1 L. M. Adleman and M. C. Loui, "Space-bounded simulation of multitape Turing machines," Math. Systems Theory, vol. 14, no. 3, pp. 215-222, July 1981.

12.2 A. Apostolico and F. P. Preparata, "Optimal off-line detection of repetitions in a string," Theoretical Computer Science (to appear).

12.3 B. S. Baker, D. J. Brown and H. P. Katseff, "A 5/4 algorithm for two-dimensional bin packing," J. Algorithms, vol. 2, pp. 348-368, 1981.

12.4 B. S. Baker, D. J. Brown and H. P. Katseff, "Lower bounds for on-line two-dimensional packing algorithms," Acta Informatica (to appear).

12.5 J. L. Bentley and D. J. Brown, "A general class of resource trade-offs," J. of Computer and System Sciences (to appear).

12.6 J. L. Bentley, M. G. Faust, and F. P. Preparata, "Approximation algorithms for convex hulls," Communications of the ACM, vol. 25, no. 1, pp. 64-68, Jan. 1982.

12.7 G. Bilardi, M. Pracchi and F. P. Preparata, "A critique of network speed in VLSI models of computation," IEEE J. of Solid State Circuits (to appear).

12.8 D. T. Lee and F. P. Preparata, "An improved algorithm for rectangle containment," J. Algorithms (to appear).

12.9 W. Lipski, Jr. and F. P. Preparata, "Efficient algorithms for finding maximum matchings in convex bipartite graphs and related problems," Acta Informatica, vol. 15, pp. 329-346, 1981.

12.10 M. C. Loui, "A space bound for one-tape multidimensional Turing machines," Theoretical Computer Science, vol. 15, no. 3, pp. 311-320, Sept. 1981.

12.11 M. C. Loui, "Simulations among multidimensional Turing machines," Theoretical Computer Science (to appear)

12.12 M. C. Loui, "Minimizing access pointers into trees and arrays," J. of Computer and System Sciences (to appear)

12.13 M. C. Loui, "Optimal dynamic embedding of trees into arrays," SIAM J. of Computing (to appear)

12.14 J. Nievergelt and F. P. Preparata, "Plane-sweep algorithms for intersecting geometric figures," Communications of the ACM (to appear).

12.15 F. P. Preparata, "A new approach to planar point location," SIAM J. of Computing, vol. 10, no. 3, pp. 473-482, Aug. 1981.

12.16 F. P. Preparata, "An area-time optimal mesh-connected multiplier for large integers," IEEE Trans. on Computing (to appear).

12.17 F. P. Preparata, "Optimal three-dimensional VLSI layouts," Mathematical System Theory (to appear).

12.18 F. P. Preparata and K. J. Supowit, "Testing a simple polygon for monotonicity," Information Processing Letters, vol. 12, no. 4, pp. 161-164, Aug. 1981.

Conference Papers

12.19 N. Ahuja and S. Swamy, "Multiprocessor pyramids for bottom-up image analysis," Proc. of the Conf. on Pattern Recognition and Image Processing, Las Vegas, NV, pp. 380-385, June 1982.

12.20 N. Ahuja and S. Swamy, "Interleaved pyramid architectures for bottom-up image analysis," Proc. of the 6th International Conf. on Pattern Recognition, Munich, Germany, Oct. 1982 (to appear).

12.21 G. Bilardi, M. Pracchi and F. P. Preparata, "A critique and an appraisal of VLSI models of computation," Proc. of CMU Conf. on VLSI Systems and Computations, Pittsburgh, PA, pp. 81-88, Oct. 1981.

12.22 D. J. Brown and R. Rivest, "New lower bounds for channel width," Proc. CMU Conf. on VLSI Systems and Computations, Pittsburgh, PA, pp. 178-185, Oct. 1981.

12.23 M. C. Loui, "Simulations among multidimensional Turing machines," Proc. of the 22nd Annual Symp. on Foundations of Computer Science, Nashville, TN, pp. 58-67, Oct. 1981.

12.24 F. P. Preparata, "An area-time optimal mesh-connected VLSI integer multiplier," Proc. CMU Conf. on VLSI Systems and Computations, Pittsburgh, PA, pp. 311-316, Oct. 1981.

Technical Reports

12.25 G. Bilardi, "Average case analysis of an adjacency map searching technique," CSL Tech. Report ACT-31, Dec. 1981.

12.26 G. Bilardi, M. Pracchi and F. P. Preparata, "A critique and an appraisal of VLSI models of computation," CSL Tech. Report ACT-28, Aug. 1981.

12.27 M. C. Loui, "Optimal dynamic embedding of trees into arrays," CSL Tech. Report ACT-29, Aug. 1981.

12.28 M. C. Loui and G. Bilardi, "The correctness of Tisan's method for generating prime implicants," CSL Tech. Report R-946, Feb. 1982.

12.29 F. P. Preparata and W. Lipski, "Optimal three-layer channel routing," CSL Tech. Report ACT-34, May 1982.

13. ADVANCED AUTOMATION

Books

13.1 N. Ahuja and B. Schachter, Pattern Models, Wiley 1982.

13.2 N. Ahuja, "Mosaic Models for Textures," in A. Rosenfeld (ed.), Image Modeling, Academic Press, pp. 1-8, 1981.

13.3 N. Ahuja and A. Rosenfeld, "Image Models," in P. R. Krishnaiah and L. N. Kanal (eds.), Handbook of Statistics, Volume 2, North Holland, 1982 (to appear).

13.4 N. Ahuja and A. Rosenfeld, "Fitting Mosaic Models to Textures," in R. M. Haralick (ed.), Image Texture Analysis, Plenum Press, 1982 (to appear).

13.5 G. F. DeJong, "An Overview of the FRUMP System," in W. Lehnert and M. Ringle (eds.), Strategies for Natural Language Processing, Lawrence Erlbaum Associates, 1982 (to appear).

13.6 R. Schank, J. Kolodner and G. DeJong, "Conceptual Information Retrieval," in R. N. Oddy, S. E. Robertson, C. J. van Rijsbergen and P. W. Williams (eds.), Information Retrieval Research, Butterworths, London, 1981.

13.7 D. L. Waltz, "The State-of-the-Art in Natural Language Understanding," in W. Lehnert and M. Ringle (eds.), Strategies for Natural Language Processing, Lawrence Erlbaum Associates, 1982 (to appear).

13.8 D. L. Waltz, "Generating and Understanding Scene Descriptions," in A. Joshi, I. Sag and B. Webber (eds.), Elements of Discourse Understanding, Cambridge University Press, pp. 266-282, 1981.

Journal Articles

13.9 N. Ahuja and B. Schachter, "Image Models," ACM Computing Surveys, pp. 373-398, Dec. 1981.

13.10 N. Ahuja, "Dot Pattern Processing Using Voronoi Neighborhoods," IEEE Trans. Pattern Analysis and Machine Intelligence, pp. 336-343, May 1982.

13.11 N. J. Bridwell and T. S. Huang, "A Discrete Spatial Representation for Lateral Motion Stereo," Computer Graphics and Image Processing (to appear).

13.12 G. F. DeJong and D. L. Waltz, "Understanding Novel Language," International Journal of Computers and Mathematics (to appear).

13.13 D. L. Waltz, "Artificial Intelligence," Scientific American (to appear).

Conference Papers

13.14 N. Ahuja, "Approaches to Recursive Image Decomposition," Proc. IEEE Conf. on Pattern Recognition and Image Processing, Dallas, pp. 75-80, Aug. 1981.

13.15 N. Ahuja, N. Bridwell, C. Nash and T. S Huang, "Three-Dimensional Robot Vision," Proc. IEEE International Workshop on Industrial Applications of Machine Vision, Raleigh-Durham, May 1982.

13.16 N. Ahuja and S. Swamy, "Multiprocessor Pyramids for Bottom-Up Image Analysis," Proc. IEEE Conf. on Pattern Recognition and Image Processing, Las Vegas, pp. 380-385, June 1982.

13.17 G. F. DeJong, "Generalizations Based on Explanations," Proc. 7th International Joint Conf. on Artificial Intelligence, Vancouver, B.C., pp. 67-69, Aug. 1981.

13.18 G. F. DeJong, "Explanatory Schema Acquisition," Proc. The National Conf. on Artificial Intelligence, Pittsburgh, Aug. 1982 (to appear).

13.19 J. Q. Fang and T. S. Huang, "A Corner Finding Algorithm for Image Analysis and Registration," Proc. The National Conf. on Artificial Intelligence, Pittsburgh, Aug. 1982 (to appear).

13.20 T. S. Huang and J. K. Cheng, "Recognition of Curvilinear Objects by Matching Relational Structures," Proc. IEEE Conf. on Pattern Recognition and Image Processing, Las Vegas, pp. 343-348, June 1982.

13.21 J. Pollack and D. L. Waltz, "Natural Language Processing Using Spreading Activation and Lateral Inhibition," Proc. 4th Annual Conf. of the Cognitive Science Society, Ann Arbor, MI, Aug. 1982 (to appear).

13.22 R. Tsai and T. S. Huang, "Uniqueness and Estimation of 3-D Motion Parameters of Rigid Objects with Curved Surfaces," Proc. IEEE Conf. on Pattern Recognition and Image Processing, Las Vegas, pp. 112-117, June 1982.

13.23 D. L. Waltz, "Toward a Detailed Model of Processing for Language Describing the Physical World," Proc. 7th International Joint Conf. on Artificial Intelligence, Vancouver, B.C., pp. 1-6, Aug. 1981.

13.24 D. L. Waltz, "Event Shape Diagrams," Proc. The National Conf. on Artificial Intelligence, Pittsburgh, Aug. 1982 (to appear).

13.25 R. Yen and T. S. Huang, "Determining 3-D Motion and Structure of a Rigid Body Using the Spherical Projection," Proc. IEEE Conf. Pattern Recognition and Image Processing, Las Vegas, pp. 599-604, June 1982.

Technical Reports and Theses

13.26 J. F. Porter, "An Algorithm for Projectile Tracking in Noise," M.S. Thesis, Univ. of Illinois, Aug. 1981.

13.27 C. G. Nash, "Translational and Rotational Manipulations of Octree Data Structures," M.S. Thesis, Univ. of Illinois, Dec. 1981.

13.28 D. L. Waltz, "ONR Annual Report," Tech. Rept. T-114, Univ. of Illinois, May 1982.

14. INFORMATION RETRIEVAL

Books

14.1 M. E. Williams, ed. Annual Review of Information Science and Technology, Vol. 16, White Plains, NY: Knowledge Industry Publications, Inc., pp. 400, 1981.

14.2 M. E. Williams, L. W. Lannom and C. G. Robins, Computer-Readable Databases: A Directory and Data Sourcebook, Washington, DC: American Society for Information Science, pp. 1516, 1982.

Journal Articles

14.3 M. E. Williams and L. W. Lannom, "Lack of standardization of the journal title data element in databases," Journal of the American Society for Information Science, vol. 32, no. 3, pp. 229-233, May 1981.

14.4 M. E. Williams and L. W. Lannom, "Previewing databases online in 1981," Bulletin of the American Society for Information Science, April 1981.

14.5 M. E. Williams, "Relative impact of print and database products on database producer expenses and income - Trends for database producer organizations based on a 13-year financial analysis," Information Processing and Management, vol. 17, no. 5, pp. 263-276, 1981.

14.6 M. E. Williams, "An analysis of online database prices and a rationale for increasing the price of Medline," Online Review, vol. 6, no. 1, pp. 7-26, Jan. 1982.

14.7 M. E. Williams, "Relative impact of print and database products on database producer expenses and income - A follow-up," Information Processing and Management (to appear).

Conference Papers

14.8 M. E. Williams, "Highlights of the online database field," National Online Meeting: Proceedings, 1981, Medford, NJ: Learned Information, Inc., pp. 1-5, 1981.

14.9 M. E. Williams and S. E. Preece, "A mini-transparent system using an alpha microprocessor," National Online Meeting: Proceedings, 1981, Medford, NJ: Learned Information, Inc., pp. 499-502, 1981.

14.10 M. E. Williams and T. H. Hogan, compilers, National Online Meeting: Proceedings, 1981, Medford, NJ: Learned Information, Inc., pp. 554 (1981).

14.11 M. E. Williams, "Highlights of the online database field in 1981," National Online Meeting: Proceedings, 1982, Medford, NJ: Learned Information, Inc., pp. 1-5, 1982.

14.12 M. E. Williams and T. H. Hogan, compilers, National Online Meeting: Proceedings, 1982, Medford, NJ: Learned Information, Inc., 1982.

15. COMMUNICATIONS

Chapters in Books

15.1 R. J. McEliece, "Some combinatorial aspects of spread-spectrum communication systems," in New Concepts in Multi-User Communications, J. K. Skwirzynski (ed.), Sijthoff and Noordhoff International Publishers, Alphen aan den Rijn, Netherlands, pp. 199-211.

15.2 M. B. Pursley, "Spread-spectrum multiple-access communications," in Multi-User Communication Systems, G. Longo (ed.), Springer-Verlag, Vienna and New York, pp. 139-199, 1981.

15.3 M. B. Pursley, "Effects of specular multipath fading on spread-spectrum communications," in New Concepts in Multi-User Communications, J. K. Skwirzynski (ed.), Sijthoff and Noordhoff International Publishers, Alphen aan den Rijn, Netherlands, pp. 481-505, 1981.

Journal Articles

15.4 S. P. Au, A. H. Haddad, and H. V. Poor, "A state estimation algorithm for linear systems driven simultaneously by Wiener and Poisson processes," IEEE Trans. on Automatic Control, vol. AC-27, pp. 617-626, June 1982.

15.5 T. Basar, "The Gaussian test channel with an intelligent jammer," IEEE Trans. on Information Theory, vol. IT-29, Jan. 1983 (to appear)

15.6 T. U. Basar and T. Basar,"Optimum coding and decoding schemes for the transmission of a stochastic process over a continuous-time stochastic channel with partially unknown statistics," Stochastics (to appear).

15.7 R. Cruz and B. Hajek, "A new upper bound to the throughput of a multi-access broadcast channel," IEEE Trans. on Information Theory, vol. IT-28, pp. 402-405, May 1982.

15.8 E. A. Geraniotis and M. B. Pursley, "Error probability for direct-sequence spread-spectrum multiple-access communications - Part II: Approximations," IEEE Trans. on Communications, vol. COM-30, pp. 985-995, May 1982.

15.9 E. A. Geraniotis and M. B. Pursley, "Error probabilities for slow-frequency-hopped spread-spectrum multiple-access communications over fading channels," IEEE Trans. on Communications, vol. COM-30, pp. 996-1009, May 1982.

15.10 R. M. F. Goodman and R. J. McEliece, "Lifetime analyses of error-control coded semiconductor RAM systems," Proc. IEE, vol. 129, pt. E, pp. 81-85, May 1982.

15.11 B. Hajek, "Information singularity and recoverability of random processes," IEEE Trans. on Information Theory, vol. IT-28, pp. 422-429, May 1982.

15.12 B. Hajek, "Stochastic equations of hyperbolic type and a two-parameter Stratonovich integral," Annals of Probability, vol. 10, pp. 451-463,May 1982.

15.13 B. Hajek, "Information of partitions with applications to random access communications," IEEE Trans. on Information Theory, vol. IT-28, Septemer 1982 (to appear).

15.14 B. Hajek and T. van Loon, "Dynamic decentralized estimation and control in a multiaccess broadcast channel," IEEE Trans. on Automatic Control, vol. 27, pp. 559-569, June 1982.

15.15 B. Hajek, "Birth-and-death processes on the integers with phases and general boundaries," J. Applied Probability, vol. 19, Sept. 1982 (to appear).

15.16 B. Hajek, "Hitting and occupation time bounds implied by drift analysis with applications," Advances in Applied Probability," vol. 14, Sept. 1982 (to appear).

15.17 D. R. Halverson, G. L. Wise, and H. V. Poor, "On the performance of two simplified approaches to memoryless discrete-time detection in dependent noise," J. of Combinatorics, Information and System Sciences, 1982 (to appear).

15.18 S. A. Kassam and H. V. Poor, "Robust signal processing for communication systems," IEEE Communications Magazine, vol. 21, Jan. 1983 (to appear).

15.19 B. H. Krogh and H. V. Poor, "The segment method as an alternative to minimax in hypothesis testing," Information Sciences, vol. 26, 1982 (to appear).

15.20 D. P. Looze, H. V. Poor, K. S. Vastola, and J. C. Darragh, "Minimax control of linear stochastic systems with noise uncertainty," IEEE Trans. on Automatic Control, vol. AC-28, March 1983 (to appear).

15.21 R. J. McEliece, B. Reznick, and J. Shearer, "A Turan inequality arising in information theory," SIAM Journal of Mathematical Analysis, vol. 12, pp. 931-934, 1981.

15.22 R. J. McEliece and D. V. Sarwate, "On sharing secrets and Reed-Solomon codes," Comm. of the ACM, vol. 24, pp. 583-584, Sept. 1981.

15.23 D. L. Michalsky, G. L. Wise, and H. V. Poor, "A relative efficiency study of some popular detectors," J. of the Franklin Institute, vol. 313, pp. 135-148, March 1982.

15.24 H. V. Poor, "Minimax linear smoothing for capacities," Annals of Probability, vol. 10, pp. 504-507, May, 1982.

15.25 H. V. Poor, "Optimum memoryless tests based on dependent data," J. of Combinatorics, Information and System Sciences, vol. 6, pp. 111-122, 1981.

15.26 H. V. Poor, "The rate-distortion function on classes of sources determined by spectral capacities," IEEE Trans. on Information Theory, vol. IT-28, pp. 19-26, Jan. 1982.

15.27 H. V. Poor, "Signal detection in the presence of weakly dependent noise - Part I: Optimum detection," IEEE Trans. on Information Theory, vol. IT-28, Sept. 1982 (to appear).

15.28 H. V. Poor, "Signal detection in the presence of weakly dependent noise - Part II: Robust detection," IEEE Trans. on Information Theory, vol. IT-28, Sept. 1982 (to appear).

15.29 H. V. Poor and D. P. Looze, "Minimax state estimation for linear stochastic systems with noise uncertainty," IEEE Trans. on Automatic Control, vol. AC-26, pp. 902-906, Aug. 1981.

15.30 M. B. Pursley, D. V. Sarwate, and W. E. Stark, "Error probability for direct-sequence spread-spectrum multiple-access communications - Part I: Upper and lower bounds," IEEE Trans. on Communications, vol. COM-30, pp. 978-984, May 1982.

15.31 D. V. Sarwate, "A note on multiple error detection in ASCII numeric data communication," J. of the ACM, (to appear).

15.32 S. Tantaratana and H. V. Poor, "Asymptotic efficiencies of truncated sequential tests," IEEE Trans. on Information Theory, vol. IT-28, Nov. 1982 (to appear).

15.33 S. Tantaratana and H. V. Poor, "A two-stage version of the Kassam-Thomas nonparametric dead-zone limiter detection system," J. of the Acoustical Society of America, vol. 71, pp. 110-115, Jan. 1982.

15.34 K. S. Vastola and H. V. Poor, "An analysis of the effects of spectral uncertainty on Wiener filtering," Automatica, vol. 19, 1983 (to appear).

15.35 S. Verdú, "Comments on 'Anomalous behavior of receiver output SNR as a predictor of signal detection performance exemplified for quadratic receivers and incoherent fading Gaussian channels'," IEEE Trans. on Information Theory, vol. IT-28, Nov. 1982 (to appear).

15.36 S. Verdú and H. V. Poor, "Minimax robust discrete-time matched filters," IEEE Trans. on Communications, vol. COM-31, 1983 (to appear).

Conference Papers

15.37 T. Basar, "The Gaussian test channel with an intelligent jammer," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, pp. 77-78, June 1982.

15.38 T. U. Basar and T. Basar, "Robust linear coding in continuous-time communication systems in the presence of jamming and with side information at the decoder," Proc. of the 1982 Conf. on Information Sciences and Systems, March 1982 (in press).

15.39 T. U. Basar and T. Basar, "Optimum coding and decoding schemes for the transmission of a stochastic process over a continuous time stochastic channel with partially unknown statistics," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, p. 51, June 1982.

15.40 J. M. Borden, D. M. Mason, and R. J. McEliece, "Some information theoretic saddlepoints," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, p. 3, June 1982.

15.41 F. D. Garber and M. B. Pursley, "Effects of selective fading on slow-frequency-hopped DPSK spread-spectrum communications," 1981 IEEE National Telecommunications Conf., Conf. Record, vol. 4, pp. G8-1.1-5, Nov. 1981.

15.42 E. A. Geraniotis, "Robust coding for classes of channels determined by 2-alternating capacities," Abstracts of papers for the 1982 IEEE International Symposium on Information Theory, pp. 76-66, June 1982.

15.43 E. A. Geraniotis, "Error probability for coherent hybrid slow-frequency-hopped direct-sequence spread-spectrum multiple-access communications," Conf. Record, IEEE National Telecommunications Conf., vol. 4, pp. G8.6.1-5, Nov. 1981.

15.44 E. A. Geraniotis and H. V. Poor, "Minimax filtering problems for observed Poisson processes with uncertain rate functions," Proc. of the 20th IEEE Conf. on Decision and Control, pp. 600-606, Dec. 1981.

15.45 E. A. Geraniotis and H. V. Poor, "Robust hypothesis testing for observed Poisson processes with uncertain rate functions," Proc. of the 1982 Conf. on Information Sciences and Systems, Princeton University, March 1982 (in press).

15.46 E. A. Geraniotis and M. B. Pursley, "Coherent direct-sequence spread spectrum communications in a specular multipath fading environment," Proc. of the 1982 Conf. on Information Sciences and Systems, Princeton University, March 1982 (in press).

15.47 E. A. Geraniotis and M. B. Pursley, "Effects of specular multipath fading on noncoherent direct-sequence spread-spectrum communications," Conf. Record, IEEE International Conf. on Communications, vol. 3, pp. 6B.5.1-5, Philadelphia, June 1982.

15.48 B. Hajek, "The proof of a folk theorem on queueing delay with applications to routing in networks," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, p. 96, June 1982.

15.49 B. Hajek, "Acknowledgement based random access retransmission control: An equilibrium analysis," IEEE International Conf. on Communication, Conf. Record, pp. IC.1.1-7, June 1982.

15.50 B. Hajek, "Recursive retransmission control - Application to a frequency-hopped spread-spectrum system," Proc. of the 1982 Conf. on Information Sciences and Systems, Princeton, March 1982 (in press).

15.51 S. A. Kassam and H. V. Poor, "A survey on robust filtering," (invited paper) Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, p. 73, June 1982.

15.52 S. M. Krone and D. V. Sarwate, "Quadriphase sequences for spread-spectrum communications," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, pp. 42-43, June 1982.

15.53 D. P. Looze, H. V. Poor, K. S. Vastola, and J. C. Darragh, "Minimax control of linear stochastic systems with noise uncertainty," Proc. of the 1982 American Control Conf., pp. 689-693, June 1982.

15.54 D. P. Looze, H. V. Poor, K. S. Vastola, and J. C. Darragh, "Minimax linear-quadratic-Gaussian control of systems with uncertain statistics," in System Modeling and Optimization: Proc. of the 10th IFIP Conf., R. F. Drenick and F. Kozin, eds., pp. 417-423, Springer-Verlag, 1982.

15.55 R. J. McEliece, "An information theorist's view of jamming problems," (invited paper) Abstracts of Papers for the IEEE International Symposium on Information Theory, p. 51, June 1982.

15.56 R. J. McEliece and M. B. Pursley, "Error-control coding for slow-frequency-hopped spread-spectrum communications," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, p. 42, June 1982.

15.57 H. V. Poor, "Distance measures in robustness," (invited paper) Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, pp. 73-74, June 1982.

15.58 M. B. Pursley, "Effects of partial correlation on the multiple-access capability of direct-sequence spread-spectrum," Conf. Record, IEEE National Telecommunications Conf., vol. 2, pp. D4.3.1-5, New Orleans, Nov. 1981.

15.59 M. B. Pursley, "Coding and diversity for channels with fading and pulsed interference," Proc. of the 1982 Conf. on Information Sciences and Systems, March 1982 (in press).

15.60 D. V. Sarwate, "Error probability bounds for a Cooper-Nettleton communication scheme," Proc. of the 1982 Conf. on Information Sciences and Systems, March 1982 (in press).

15.61 W. E. Stark, "Performance of concatenated codes on channels with jamming," Conf. Record, 1982 IEEE International Conf. on Communications, pp. 7E.4.1-5, June 1982.

15.62 W. E. Stark and R. J. McEliece, "Capacity and coding in the presence of fading and jamming," 1981 IEEE National Telecommunications Conf., Conf. Record, pp. B7.4.1-5, Nov. 1981.

15.63 S. Verdú and H. V. Poor, "A general approach to the estimation and control of linear systems with nôise uncertainty," Proc. of the 1982 Conf. on Information Sciences and Systems, Princeton University, March 1982 (in press).

15.64 S. Verdú and H. V. Poor, "General results on minimax robust filtering," Abstracts of Papers for the 1982 IEEE International Symposium on Information Theory, p. 124, June 1982.

15.65 S. Verdú and H. V. Poor, "Least favorable signals and noise for discrete-time robust matched filtering," 1981 IEEE National Telecommunications Conf., Conf. Record, pp. 8.2.1-5, Nov./Dec. 1981.

Technical Reports:

15.66 H. V. Poor and S. Tantaratana, "A useful class of multistage tests," Technical Report No. R-923, Coordinated Science Laboratory, UIUC, Dec. 1981.

15.67 S. Verdú, "A general approach to minimax robust filtering," Technical Report No. R-933, Coordinated Science Laboratory, UIUC, Dec. 1981.

16. ANALOG AND DIGITAL CIRCUITS

Books

16.1 I. N. Hajj, "Computer-aided circuit analysis and design," in Handbook of Electrical and Computer Engineering, John Wiley and Sons, Inc., (in press).

16.2 T. N. Trick, W. Mayeda, and A. A. Sakla, "Calculation of parameter values from node voltage measurements," in The World of Large Scale Systems, IEEE Press, (1982).

Journal Articles

16.3 R. D. Davis, "A derivation of the switched-capacitor adjoint network based on a modified Tellegen's theorem," IEEE Trans. on Circuits and Systems, vol. CAS-29, pp. 215-220, Apr. 1982.

16.4 E. I. El-Masry, "An analytic solution of the Fokker-Planck Equation in the absence of noise," IEEE Proc., vol. 70, pp. 519-520, May 1982.

16.5 F. B. Grosz, Jr. and T. N. Trick, "Some modifications to Newton's method for the determination of the steady state response of nonlinear oscillatory circuits," IEEE Trans. on Computer-aided Design of Integrated Circuits and Systems, vol. CAD-1, July 1982.

16.6 D. E. Hocevar and T. N. Trick, "Automatic tuning algorithms for active filters," IEEE Trans. on Circuits and Systems, vol. CAS-29, Aug. 1982

16.7 C. F. Lee and W. K. Jenkins, "Computer-aided analysis of switched capacitor filters," IEEE Trans. on Circuits and Systems, vol. CAS-28, No. 7, pp. 132-133, July 1981.

16.8 C. F. Lee and W. K. Jenkins, "Programming techniques for computer-aided analysis of switched capacitor circuits based on modified nodal analysis," IEEE Trans. on Circuits and Systems, vol. CAS-30, no. 2, Feb. 1983 (to appear).

16.9 M. R. Lightner and S. W. Director, "Multiple criterion optimization with yield maximization," IEEE Trans. on Circuits and Systems, vol. CAS-28, pp. 781-791, Aug. 1981.

Conference Papers

16.10 N. Attaie and E. I. El-Masry, "Optimized multiple-loop feedback switched-capacitor structures," Proc. Fifteenth Asilomar Conf. on Circuits, Systems and Computers, Pacific Grove, CA, pp. 285-289, Nov. 1981.

16.11 N. Attaie and E. I. El-Masry, "A low-sensitivity switched-capacitor filter structure," Proc. 1982 IEEE International Symposium on Circuits and Systems, Rome, Italy, pp. 451-454, May 1982.

16.12 R. D. Davis, T. N. Trick, and W. K. Jenkins, "An efficient LU factorization scheme for the analysis of switched-capacitor filters," Proc. of IEEE International Symposium on Circuits and Systems, pp. 975-978, May 10-12, 1982.

16.13 R. D. Davis, T. N. Trick, and W. K. Jenkins, 'SCAPN: An N-phased switched-capacitor circuit analysis program," Proc. of the Fifteenth Annual Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, CA, pp. 484-488, Nov. 1981.

16.14 I. N. Hajj, "Decomposition algorithms for the shortest path problem," Proc. of IEEE International Symposium on Circuits and Systems, pp. 975-978, May 10-12, 1982.

16.15 W. K. Jenkins and C. F. Lee, "An example of switched-capacitor filter analysis with SCAPII," Proc. of the 1981 European Conf. on Circuit Theory and Design, The Hague, Netherlands, pp. 1082-1082, Aug. 1981.

16.16 M. R. Lightner and G. D. Hachtel, "MOS switch level simulation, macromodeling, and testing," Proc. IEEE International Symposium on Circuits and Systems, pp. 6367, May 10-12, 1982.

16.17 M. R. Lightner and G. D. Hachtel, "Implication algoritms for MOS switch level functional macromodeling, extraction, and testing," ACM IEEE Nineteenth Design Automation Conf., June 14-16. 1982.

16.18 W. Mayeda, "On partitioning a network into blocks for diagnosis," Fifteenth Asilomar Conf. on Circuits, Systems, and Computers, pp. 11-13, Nov. 9-11, 1982.

16.19 V. B. Rao, T. N. Trick, and M. R. Lightner, "Hazard detection in a multiple delay logic simulator," Proc. of IEEE International Symposium on Circuits and Systems, pp. 72-75, May 10-12, 1982.

16.20 P. Yang, I. N. Hajj, and T. N. Trick, "Tearing and multilevel exploitation of latency in a circuit simulation program," Proc. of European Conf. on Circuit Theory and Design, North Holland Publishing Company, Amsterdam, pp. 157-163, Aug. 1981.

Technical Reports and Theses

16.21 N. Attaie, "Optimized structures for switched-capacitor filters," Coordinated Science Laboratory Report R-934, University of Illinois, Urbana, IL, October 1981.

16.22 R. D. Davis, "Computer analysis of switched-capacitor filters including sensitivity and distortion effects," Ph.D. Thesis, Department of Electrical Engineering, University of Illinois at Urbana-Champaign, Oct. 1981.

16.23 M. M. Hanlon, "Simulating switched-capacitor filter noise using circuit analysis programs," M.S. Thesis, Department of Electrical Engineering, University of Illinois at Urbana-Champaign, Oct. 1981.

16.24 D. E. Hocevar, "Automatic tuning algorithms and statistical circuit design," Ph.D. Thesis, Department of Electrical Engineering, University of Illinois at Urbana-Champaign, June 1982.

16.25 C. N. Lam, "The analysis and design of a CMOS operational amplifier," M. S. Thesis, Department of Electrical Engineering, University of Illinois at Urbana-Champaign, June 1982.

16.26 V. B. Rao, "Algorithms for a multiple-delay simulator," M. S. Thesis, Department of Electrical Engineering, University of Illinois at Urbana-Champaign, May 1982.

16.27 J. H. Stothoff, "State space design of MOS sampled-data filters," M. S. Thesis, University of Illinois, Urbana, IL, Oct. 1981.

17. DECISION AND CONTROL

Books

17.1 Tamer Basar and G. J. Olsder, Dynamic Noncooperative Game Theory, Academic Press, London/New York, 1982.

Book Chapters

17.2 Tamer Basar and J. B. Cruz, Jr., "Concepts and methods in multiperson coordination and control," in Optimization and Control of Dynamic Operational Research Models, S. G. Tzafestas (Ed.), North Holland, 1982.

17.3 H. Salhi and D. P. Looze, "A decomposition algorithm for a second order elliptic operator using asymptotic expansions," in System Modeling and Optimization, R. F. Drenick and F. Kozin, (Eds.), Springer-Verlag, New York, pp. 374-383, 1982.

Journal Articles

17.4 S. Ahmed-Zaid, P. W. Sauer, M. A. Pai and M. K. Sarioglu, "Reduced order modelling of synchronous machines using singular perturbation," IEEE Trans. on Circuits and Systems (to appear).

17.5 A. Bagchi and Tamer Basar, "Stackelberg strategies in linear-quadratic stochastic differential games," J. of Optimization Theory and Applications, vol. 35, no. 3, pp. 443-464, Nov. 1981.

17.6 Tamer Basar, "Equilibrium strategies in dynamic games with multi-levels of hierarchy," Automatica, vol. 17, no. 5, pp. 749-754, 1981.

17.7 Tamer Basar, "A general theory for Stackelberg games with partial state information," Large Scale Systems, vol. 3, no. 1, pp. 47-56, Jan. 1982.

17.8 T. Basar, "Performance bounds for hierarchical systems under partial dynamic information," J. of Optimization Theory and Applications, 1982 (to appear).

17.9 Tamer Basar, "The Gaussian test channel with an intelligent jammer," IEEE Trans. on Information Theory, vol. IT-28, no. 1, Jan. 1983 (to appear).

17.10 T. U. Basar and Tamer Basar, "Optimum coding and decoding schemes for the transmission of a stochastic process over a continuous-time stochastic channel with partially unknown statistics," Stochastics, 1983 (to appear).

17.11 A. Bensoussan, "Singular perturbation results for a class of stochastic control problems," IEEE Trans. on Automatic Control, vol. AC-26, No. 5, pp. 1071-1080, Oct. 1981.

17.12 D. Cobb, "On the solutions of linear differential equations with singular coefficients," J. of Differential Equations, 1982 (to appear).

17.13 D. Cobb, "Descriptor variable systems and optimal state regulation," IEEE Trans. on Automatic Control, 1982 (to appear).

17.14 J. B. Cruz, Jr., D. P. Looze and W. R. Perkins, "Sensitivity analysis of nonlinear feedback systems," J. of the Franklin Institute, vol. 312, no. 3/4, pp. 199-215, Sept./Oct. 1981.

17.15 J. D. Darragh and D. P. Looze, "Noncausal minimax state estimation for systems with uncertain second order statistics," IEEE Trans. on Automatic Control (to appear).

17.16 J. S. Freudenberg, D. P. Looze and J. B. Cruz, Jr., "robustness analysis using singular value sensitivities," International J. of Control, vol. 35, no. 1, pp. 93-116, Jan. 1982.

17.17 W. E. Hopkins, J. Medanic and W. R. Perkins, "Output-feedback pole placement in the design of suboptimal linear quadratic regulators," International J. of Control, vol. 34, no. 3, pp. 593-612, 1981.

17.18 P. A. Ioannou, "Robustness of absolute stability," International J. of Control, vol. 34, no. 5, pp. 1027-1033, 1981.

17.19 Petros Ioannou and C. Richard Johnson, Jr., "Reduced-order performance of parallel and series-parallel identifiers with respect to weakly observable parasitics," Automatica, 1982 (to appear).

17.20 P. A Ioannou and P. V. Kokotovic, "An asymptotic error analysis of identifiers and adaptive observers in the presence of parasitics," IEEE Trans. on Automatic Control, Aug. 1982 (to appear).

17.21 T. W. Kay, P. W. Sauer, R. D. Shultz and R. A. Smith, "EHV and UHV line loadability dependence on VAR supply capability," IEEE Trans. on Power Apparatus and Systems, (to appear).

17.22 P. V. Kokotovic, "Subsystems, time scales, and multimodeling," Automatica, vol. 17, no. 6, pp. 789-795, 1981.

17.23 P. V. Kokotovic, B. Avramovic, J. H. Chow and J. R. Winkelman, "Coherency based decomposition and aggregation," Automatica, vol. 18, no. 1, pp. 47-56, Jan. 1982.

17.24 B. H. Krogh and H. V. Poor, "The segment method as an alternative to minimax in hypothesis testing," Information Sciences 1982 (to appear).

17.25 D. Lindner, W. R. Perkins and J. Medanic, "Chained aggregation and three-control-component design: A geometric analysis," Int. J. of Control, vol. 35, no. 4, pp. 621-635, 1982.

17.26 D. P. Looze, "A dual optimization procedure for linear quadratic control problems," Automatica (to appear).

17.27 D. P. Looze and N. R. Sandell, Jr., "Hierarchical control of weakly coupled systems," Automatica (to appear).

17.28 D. P. Looze and N. R. Sandell, Jr., "Analysis of decomposition algorithms via nonlinear splitting functions," J. of Optimization Theory and Applications, vol. 34, no. 3, pp. 371-382, July 1981.

17.29 D. P. Looze, H. V. Poor, K. S. Vastola and J. C. Darragh, "Minimax control of linear stochastic systems with noise uncertainty," IEEE Trans. on Automatic Control (to appear).

17.30 M. Mansour, "A note on the stability of linear discrete systems and Lyapunov method," IEEE Trans. on Automatic Control, vol. AC-27, no. 3, June 1982 (to appear).

17.31 R. G. Phillips and P. V. Kokotovic, "A singular perturbation approach to modeling and control of Markov chains," IEEE Trans. on Automatic Control, vol. AC-26, no. 5, pp. 1087-1094, Oct. 1981.

17.32 H. Vincent Poor and Douglas P. Looze, "Minimax state estimation for linear stochastic systems with noise uncertainty," IEEE Trans. on Automatic Control, vol. AC-26, pp. 902-906, Aug. 1981.

17.33 V. R. Saksena and T. Basar, "Multimodel approach to stochastic team problems," Automatica, vol. 18, no. 6, Nov. 1982 (to appear).

17.34 V. Saksena and J. B. Cruz, Jr., "Nash strategies in decentralized control of multiparameter singularly perturbed large scale systems," Large Scale Systems, vol. 2, no. 4, pp. 219-234, Nov. 1981.

17.35 V. R. Saksena and J. B. Cruz, Jr., "A multimodel approach to stochastic Nash games," Automatica, vol. 18, no. 3, pp. 295-305, 1982.

17.36 V. R. Saksena and P. V. Kokotovic, "Singular perturbation of the Popov-Kalman-Yakubovich lemma," systems & Control Letters, vol. 1, no. 1, pp. 65-68, July 1981.

17.37 M. A. Salman and J. B. Cruz, Jr., "An incentive model of duopoly with government coordination," Automatica, vol. 17, no. 6, pp. 821-829, Nov. 1981.

17.38 P. W. Sauer, "Explicit load flow series and functions," IEEE Trans. on Power Apparatus and Systems, vol. PAS-100, no. 8, pp. 3754-3764, Aug. 1981. Summary published in IEEE Power Engineering Society Review, vol. PER-1, no. 8, p. 37, Aug. 1981.

17.39 P. W. Sauer and B. Hoveida, "Constrained stochastic power flow analysis," International J. of Electric Power Systems Research (to appear).

17.40 K. K. D. Young and P. V. Kokotovic, "Analysis of feedback loop interactions with actuator and sensor parasitics," Automatica (to appear).

17.41 Ying-Ping Zheng and Tamer Basar, "Existence and derivation of optimal affine incentive schemes for Stackelberg games with partial information: A geometric approach," International J. of Control, vol. 35, no. 6, pp. 997-1012, June 1982.

Conference Papers

17.42 S. Ahmed-Zaid and P. W. Sauer, "Optimal system loadability," Proc. of the 1981 Midwest Power Symposium, Urbana, IL, sec. 3.1, pp. 1-10, Oct. 1981.

17.43 A. Bagchi, R. C. Strijbos and Tamer Basar, "New formulas for open and closed-loop LQ control laws and related numerical considerations," Proc. of the IFAC Symposium on the Theory and Applications of Digital Control, New Delhi, India, Jan. 1982.

17.44 Tamer Basar, "A new method for the Stackelberg solution of differential games with sampled-date state information," IVAC/81 Congress, Kyoto, Japan, pp. IX-139 to IX-144, Aug. 1981.

17.45 T. Basar, "Performance bounds for hierarchical systems under partial dynamic information," Proc. of the 20th IEEE Conf. on Decision and Control, San Diego, Calif., pp. 1133-1138, Dec. 1981.

17.46 Tamer Basar, "The Gaussian test channel with an intelligent jammer," IEEE International Symposium on Information Theory, Les Arcs, France, June 1982.

17.47 Tamer Basar, "An equilibrium theory for multi-person multi-criteria stochastic decision problems with multiple subjective probability measures," Proc. of the Ninth Prague Conf. on Information Theory, Statistical Decision Functions and Random Processes, Prague, Czechoslovakia, 1983 (to appear).

17.48 Tamer Basar, "Affine incentive schemes for stochastic systems with dynamic information," Proc. of the 1982 American Control Conf., Arlington, Virginia, June 1982.

17.49 Tangul U. Basar and Tamer Basar, "Optimum coding and decoding schemes for the transmission of a stochastic process over a continuous-time stochastic channel with partially unknown statistics," IEEE International Symposium on Information Theory, Les Arcs, France, June 1982.

17.50 Tangul U. Basar and Tamer Basar, "Robust linear coding in continuous-time communication systems in the presence of jamming and with noise side information at the decoder," Proc. of the 16th Princeton Conf. on Information Science and Systems, Princeton, NJ, March 1982.

17.51 Tamer Basar and Alain Haurie, "New thoughts on feedback Stackelberg strategies," Optimization Days 1981, Montreal, Canada, May 1982.

17.52 Derya Conever and Tamer Basar, "A minimum sensitivity approach to incentive design problems," to be presented at the 1982 Decision and Control Conf., Dec. 1982.

17.53 Y. M. Chan and J. B. Cruz, Jr., "Self-tuning methods for multicontroller systems," Proc. of the 1982 American Control Conf., Arlington, VA, June 1982.

17.54 J. C. Darragh and D. P. Looze, "Noncausal minimax state estimation for systems with uncertain second order statistics," 21st IEEE Conf. on Decision and Control (to appear).

17.55 F. Delebecque, J. P. Quadrat and P. V. Kokotovic, "Aggregability of dynamic systems and lumpability of Markov chains," Proc. of the 20th IEEE Conf. on Decision and Control, San Diego, Calif., pp. 199-203, Dec. 1981.

17.56 J. S. Freudenberg, D. P. Looze and J. B. Cruz, Jr., "Robustness analysis using singular value sensitivities," Proc. of the 20th IEEE Conf. on Decision and Control, San Diego, Calif., pp. 1158-1166, Dec. 1981.

17.57 M. Fuerst and P. W. Sauer, "Optimal system loadability," Proc. of the 1981 Midwest Power Symposium, Urbana, IL, sec. 3.1, pp. 1-10, Oct. 1981.

17.58 P. A. Ioannou and P. V. Kokotovic, "Error bounds for model-plant mismatch in identifier and adaptive observers," Proc. JACC, Charlottesville, VA, paper WA-4D, June 1981.

17.59 P. V. Kokotovic, B. Avramovic, J. H. Chow and J. R. Winkelman, "Coherency based decomposition and aggregation of a class of large scale systems," 8th World Congress of IFAC, Kyoto, Japan, vol. IX, pp. IX-52 to IX-60, Aug. 1981.

17.60 P. V. Kokotovic and P. A. Ioannou, "Robustness redesign of continuous-time adaptive schemes," 20th IEEE Conf. on Decision and Control, San Diego, CA, pp. 522-527, Dec. 1981.

17.61 J. H. Lin, R. D. Shultz, R. A. Smith and P. W. Sauer, "China's energy challenges," Proc. of the 1982 American Power Conf., April 1982.

17.62 Douglas Lindner, William R. Perkins and Juraj V. Medanic, "Chained aggregation: A geometric analysis," 8th World Congress of IFAC, Kyoto, Japan, pp. IX-92 to IX-97, Aug. 1981.

17.63 D. Lindner, W. R. Perkins and J. Medanic, "Near unobservability in singularly perturbed systems," IFAC Workshop on Singular Perturbations and Robustness of Control Systems, Ohrid, Yugoslavia, July 1982.

17.64 D. P. Looze, H. V. Poor, K. S. Vastola and J. C. Darragh, "On linear-quadratic-Gaussian control of systems with uncertain noise statistics," in System Modeling and Optimization, R. F. Drenick and F. Kozin, eds, Springer-Verlag, New York, 1982, pp. 417-423.

17.65 D. P. Looze, H. V. Poor, K. S. Vastola and J. C. Darragh, "Minimax control of linear stochastic systems with noise uncertainty," 1982 ACC, Arlington, VA, June 1982 (to appear).

17.66 Douglas P. Looze and Hassen Salhi, "Decomposition and aggregation in hierarchical systems," 8th World Congress of IFAC, Kyoto, Japan, pp. IX-110 to IX-114, Aug. 1981.

17.67 R. S. McEwen and D. P. Looze, "Quadratic weight adjustment for the enhancement of feedback properties," Proc. of the 1982 ACC, Arlington, VA, June 1982 (to appear).

17.68 R. A. Padilla, J. B. Cruz, Jr., C. S. Padilla and R. Milito, "On adaptive Nash games," 8th World Congress of IFAC, Kyoto, Japan, vol. IX, pp. 151-156, Aug. 1981.

17.69 G. Peponides, P. V. Kokotovic and J. H. Chow, "Singular perturbations and time scales in nonlinear models of power systems," International Symposium on Circuits and Systems, Rome, Italy, May 1982.

17.70 W. R. Perkins, J. B. Cruz, Jr., and J. Benhabib, "Achieving social goals in oligopolies by government incentives," 1982 Conf. on Economic Dynamics and Control, Washington, D. C., June 1982.

17.71 S. Renjen and D. P. Looze, "Analysis of on-line microprocessor based control," Proc. of the Fifteenth Asilomar Conf. on Circuits, Systems, and Computation, Pacific Grove, CA, Nov. 1981.

17.72 S. Renjen and D. P. Looze, "Synthesis of decentralized output/state regulators," 1982 ACC, Arlington, VA, June 1982.

17.73 V. R. Saksena and Tamer Basar, "A multimodel approach to stochastic team problems," IFAC Workshop on Singular Perturbations and Robustness of Control Systems, Obrid, Yugoslavia, July 1982 (to be presented).

17.74 M. A. Salman and J. B. Cruz, Jr., "Information structure, optimal coordination, and a game model of duopoly," 8th World Congress of IFAC, Kyoto, Japan, Vol. IX, pp. 157-162, Aug. 1981.

17.75 K. K. D. Young and P. V. Kokotovic, "An asymptotic analysis of interactions of feedback loops with parasitics in actuators and sensors," 8th World Congress of IFAC, Kyoto, Japan, Vol. IV, pp. IV-18 to IV-24, Aug. 1981.

18. DIGITAL SIGNAL AND IMAGE PROCESSING

Journal Articles

18.1 G. Cortelazzo and M. R. Lightner, "On the design of digital filters with monotonic transition regions using 'don't care' bands," Trans. of the Illinois State Academy of Science (to appear).

18.2 M. H. Etzel and W. K. Jenkins, "The design of specialized residue classes for efficient recursive digital filter realization," IEEE Trans. on Acoustics, Speech, and Signal Processing, vol. ASSP-30, pp. 370-380, June 1982.

18.3 W. E. Higgins and D. C. Munson, Jr., "Noise reduction strategies for digital filters: Error spectrum shaping versus the optimal linear state-space structure," IEEE Trans. on Acoustics, Speech, and Signal Processing (to appear).

18.4 B. Liu and D. C. Munson, Jr., "Generation of a random sequence having a jointly specified marginal distribution and autocovariance," IEEE Trans. on Acoustics, Speech, and Signal Processing (to appear).

18.5 D. C. Munson, Jr., "Accessibility of zero-input limit cycles," IEEE Trans. on Acoustics, Speech, and Signal Processing, vol. ASSP-29, pp. 1027-1032, Oct. 1981.

18.6 D. C. Munson, Jr. and Y. K. Hwang, "Verification of quantization error formulas for ROM/ACC filters: Comment on 'Low-noise realizations for narrow-band recursive digital filters'," IEEE Trans. on Acoustics, Speech, and Signal Processing (to appear).

18.7 D. C. Munson, Jr. and B. Liu, "Floating point roundoff error in the prime factor FFT," IEEE Trans. on Acoustics, Speech, and Signal Processing, vol. ASSP-29, pp. 877-882, Aug. 1981.

18.8 R. Y. Tsai and T. S. Huang, "Estimating three-dimensional motion parameters of a rigid planar patch," IEEE Trans. on Acoustics, Speech, and Signal Processing, vol. ASSP-29, 1147-1152, Dec. 1981.

18.9 R. Y. Tsai, T. S. Huang, and W. L. Zhu, "Estimating three-dimensional motion parameters of a rigid planar patch II: Singular value decomposition," IEEE Trans. on Acoustics, Speech, and Signal Processing (to appear).

Conference Papers

18.10 A. C. Bovik, T. S. Huang, and D. C. Munson, Jr., "Nonlinear filtering using linear combinations of order statistics," Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 2067-2070, May 1982.

18.11 G. Cortelazzo and M. R. Lightner, "The use of multiple criterion optimization for the simultaneous phase and magnitude design of IIR digital filters," Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 1813-1816, May 1982.

18.12 D. A. Hayner, S. Renjen, T. S. Huang, and W. K. Jenkins, "Algorithms and experimental results on image reconstruction from limited data," Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 1557-1560, May 1982.

18.13 W. E. Higgins and D. C. Munson, Jr., "Optimal error spectrum shaping for cascade-form digital filters," Proc. of the 1982 IEEE International Symposium on Circuits and Systems, Rome, pp. 1029-1032, May 1982.

18.14 T. S. Huang, Y. P. Hsu and R. Y. Tsai, "Interframe image coding by general two-dimensional motion compensation, Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 464-467, May 1982.

18.15 W. K. Jenkins, "Failure resistant digital filters based on residue number system product codes," Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 60-63, May 1982.

18.16 W. K. Jenkins, "A new approach to the design of an error checker for failure resistant residue number digital filters," Proc. of the 1982 IEEE International Symposium on Circuits and Systems, Rome, pp. 369-372, May 1982.

18.17 D. C. Munson, Jr. and W. K. Jenkins, "A common framework for spotlight mode synthetic aperture radar and computer-aided tomography," Proc. of the 15th Annual Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, CA, pp. 217-221, Nov. 1981.

18.18 D. C. Munson, Jr. and E. C. Martin, "Sampling rates for linear shift-variant discrete-time systems," Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 488-491, May 1982.

18.19 R. Y. Tsai and T. S. Huang, "Uniqueness and estimation of three-dimensional motion parameters of a rigid planar patch from three perspective views," Proc. of the 1982 IEEE International Conf. on Acoustics, Speech, and Signal Processing, Paris, pp. 834-837, May 1982.

Technical Reports and Theses

18.20 A. C. Bovik, "Nonlinear filtering using linear combinations of order statistics," Coordinated Science Laboratory Report R-935, University of Illinois, 1982.

18.21 A. J. Brown, "Capabilities of the INTEL-2920 for digital filtering," M.S. Thesis, Department of Electrical Engineering, University of Illinois, 1981.

18.22 W. F. Kappauf, "Analysis and simulation of an adaptive noise canceller," M.S. Thesis, Department of Electrical Engineering, University of Illinois, 1982.

18.23 D. G. Payne, "Design of a digital controller with analysis and simulation of quantization effects," M.S. Thesis, Department of Electrical Engineering, University of Illinois, 1982.

18.24 R. C. Rose, "An additive synthesis electronic music machine," M.S. Thesis, Department of Electrical Engineering, University of Illinois, 1981.

18.25 J. H. Strickland, Jr., "Maximum amplitude zero-input limit cycles in digital filters," M.S. Thesis, Department of Electrical Engineering, University of Illinois, 1981.

18.26 R. Y. Tsai, "Uniqueness and estimation of 3-D motion parameters of rigid objects," Ph.D. Thesis, Department of Electrical Engineering, University of Illinois, 1981.

1. MOLECULAR BEAM EPITAXY

Faculty and Senior Staff

A. Y. Cho	K. Hess	H. Morkoc
J. D. Dow	M. V. Klein	G. E. Stillman
J. E. Greene		B. G. Streetman

Graduate Students

D. Arnold	J. Klem	A. Rockett
T. J. Drummond	W. Kopp	S. L. Su
R. Fischer	W. G. Lyons	R. E. Thorne

1.1 Molecular Beam Epitaxy*

This is a research program involving many aspects of semiconductor research and molecular beam epitaxy. The research effort includes materials growth by MBE, studies of basic electronic and optical properties of layered structures and applications to high speed electronic devices. The objective is to utilize the unique features of MBE in the preparation of novel structures and to explore new opportunities for devices.

In this period, the research on $Al_xGa_{1-x}As$/GaAs single and multiple interface structures continued. In addition, we began studying the incorporation of Si both in GaAs and $Al_xGa_{1-x}As$.

Multiple interface heterojunctions with GaAs layers as thin as 25 Å were grown in a wide range of growth temperatures. The photoluminescence intensity associated with the quantum wells was very low for substrate growth temperatures below about 650°C and improved steadily as the substrate temperature increased to 700°C. The principal electron to heavy hole transition appeared to have shifted downward in energy unless the structure was grown at about 700°C. Above 700°C, the emission from the quantum wells

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424.

diminished entirely while that from the $Al_xGa_{1-x}As$ improved steadily with increasing substrate temperature. The overall conclusion of this study is that the heterointerfacial properties are very important and dominate the luminescence spectra. Investigations of the single interface structures with the binary on top of ternary, and the ternary on top of binary showed a substantial anisotropy. While it is relatively easy to obtain good interfaces when the $Al_xGa_{1-x}As$ layer is grown on top of GaAs, the reverse is not always reproducible and requires a precise set of growth conditions, the most dominant growth parameter being the substrate temperature. At a substrate temperature of 700°C, the atomic surface morphology of the $Al_xGa_{1-x}As$ is best, leading to a specular heterointerface. This interface roughness is responsible for the low PL intensity as well as the shift in energy.

The rough surface of the $Al_xGa_{1-x}As$ layer can be improved by growing a thin, e.g., 50 Å, GaAs layer. As a result of this smoothing effect, the multiple interface structures are expected to be a little less sensitive to the growth conditions than the single well heterojunction structure. The use of a smoothing layer to relax the growth conditions without the loss of quality was demonstrated using GaAs FETs on $Al_xGa_{1-x}As$ buffer layers.

Incorporation of donor impurities in $Al_xGa_{1-x}As$ was also investigated. Particular emphasis was placed on Si because the other most commonly used donor, Sn, evaporates quite readly from the surface at high substrate temperatures. Both electrical measurements and secondary ion mass spectroscopy techniques were used to characterize the films. A substrate temperature range of 600 - 720°C, mole fractions between 0 and 1.0 and electron concentrations of 10^{16} - 5 x 10^{18} cm^{-3} were investigated. It was discovered that caution must be exercised in determining the donor activation energy from the n vs T measurements. The modulation doping effect can lead to anomalously high activation energies. Unlike Sn, the activation energy of Si in $Al_xGa_{1-x}As$ was small, ~ 15 eV, except for some deepening at about x =.5.

1.2 Modulation Doped $Al_xGa_{1-x}As$/GaAs FETs*

Selectively doped $Al_xGa_{1-x}As$/GaAs heterostructures where only the larger

* This work was supported by the U. S. Air Force Office of Scientific Research under contract AFOSR 80-0084.

bandgap material is doped with a suitable donor are of special importance from the standpoint of studies of basic phenomena and device applications. The objectives of this program are to study in detail the low and high field transport parallel to the heterointerface and to fabricate short channel FETs for switching applications.

During the last period our investigation of single and multiple interface undoped and modulation doped GaAs/$Al_xGa_{1-x}As$ heterostructures was undertaken. This program differs from our other work in that the objective is geared toward FETs. Primarily, the electrical properties of single interface modulation doped structures and optical properties of undoped multiple interface structures were studied. In addition, by measuring transport properties parallel to the heterointerface for a number of structures grown under different conditions, the optimum MBE growth conditions were determined for both binary-on-ternary and ternary-on-binary structures. Structures with the ternary on top of binary exhibited much better performance and thus were used to fabricate FETs. The thickness of the undoped separation layer in these structures was adjusted to provide an optimum donor/electron separation for FET operation.

Optimized normally-off modulation doped FETs with 3 μm channel lengths and 1 μm gate lengths displayed transconductances as high as 250 mS/mm at 300 K. This figure is expected to double at 77 K. It is predicted that such a FET will exhibit a switching time of 8 psec in a ring oscillator configuration at 300 K. Needless to say, operating parameters such as load resistance and power supply voltage must be optimized to achieve this performance.

2. SEMICONDUCTOR MATERIALS AND DEVICES

Faculty and Senior Staff

G. E. Stillman

Graduate Students

G. E. Bulman
L. W. Cook
M. A. Haase
M. H. Kim
T. R. Lepkowski
T. S. Lo
V. M. Robbins
T. J. Roth
D. S. Ruby
B. J. Skromme
N. Tabatabaie
M. M. Tashima
T. H. Windhorn

2.1 Introduction

The primary goal of this research is to evaluate the potential of high-purity InP and InGaAsP (including the ternary limit of this lattice-matched quaternary alloy system) for optical and microwave device applications. The thrust of the JSEP supported work is to investigate the hydride growth technique for the growth of InP and InGaAsP. This process is particularly interesting because it permits easy control of the III-V ratio, in contrast to the PCl_3 (chloride) growth technique, and because the growth of P containing compounds seems to be much more controllable when contrasted to the popular MOCVD and MBE growth techniques. With other support, LPE growth of InP and InGaAsP is also being studied, and the properties of the hydride-VPE and LPE epitaxial layers are compared. The techniques used in this work to characterize the material include the measurement and analysis of Hall coefficients and resistivity measurements over the 4-350 K temperature range to determine the total concentrations of electrically active donors and acceptors. The influence of the growth conditions on the identity and concentration of the acceptor species incorporated in the epitaxial layers is studied through photoluminescence measurements over the 1.5-20 K range. Deep levels, and the influence of different growth parameters on the concentrations and energy levels of these centers are studied through DLTS measurements. The

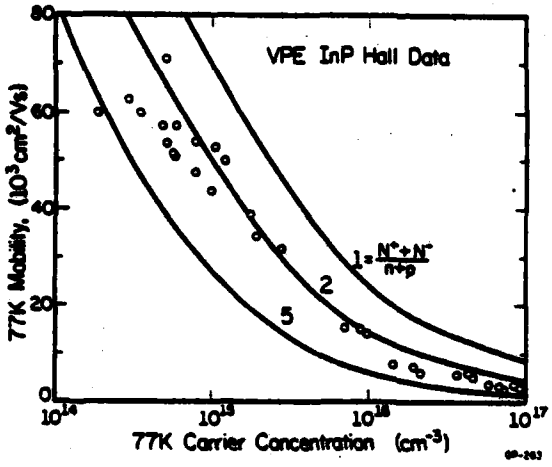
crystalline quality and degree of lattice match are studied with an x-ray diffractometer purchased with partial support using JSEP funds. The residual shallow donor impurities in InP are studied using far infrared Fourier transform measurements of photothermal ionization photoconductivity on high purity epitaxial InP.

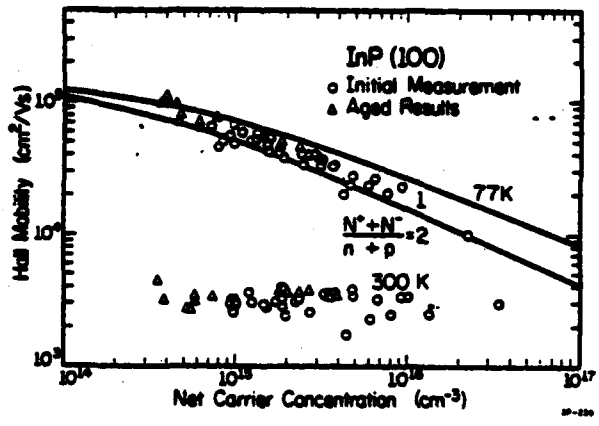
2.2 Hydride Vapor Phase Growth of High Purity InP*

The most common figure of merit cited for high purity InP is the majority carrier mobility at 77 K. The carrier concentration and the mobility are generally derived from the Hall coefficient and resistivity. There is a danger in using the 77 K mobility as the sole indication of sample purity in that the measurement technique averages the Hall constant and sample resistivity over the sample. The electrical data obtained from the van der Pauw technique are of some use in detecting inhomogeneities. In a homogeneous sample, the ratios of resistanes measured on a van der Pauw-Hall effect sample by permuting contacts should be determined by sample and contact geometry only. They should be the same at 77 K and 300 K. Inhomogeneities in impurity concentration across the wafer can cause differences in these ratios at the different temperatures. When proper caution is exercised, the 77 K mobility is a useful measure of the sample quality. The 77 K carrier concentration and the compensation curves calculated for InP, [R1] provide an estimate of the concentration of electrically active donors and acceptors in the crystal. Figure 2.1 shows the 77 K mobilities of a number of VPE hydride grown samples for a wide range of carrier concentrations as well as the corresponding theoretical curves of Rode [R1]. The data points generally follow the curve for $(N^+ + N^-)/(n + p) = 2$ indicating that the concentration of donors is approximately three times that of acceptors. By contrast, high purity InP grown by LPE appears to be nearly uncompensated.

Table 2.1 is a compilation of the 77 K and 300 K Hall data for the ten best InP layers grown by VPE in our lab. Also included for comparison are the highest mobility VPE samples, both halide, reported in the literature. The 71,000 cm^2/V-sec layer, VPE I-221 is the highest mobility reported to date for

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contracts DAAG-29-78-C-0016 and N00014-79-C-0424.





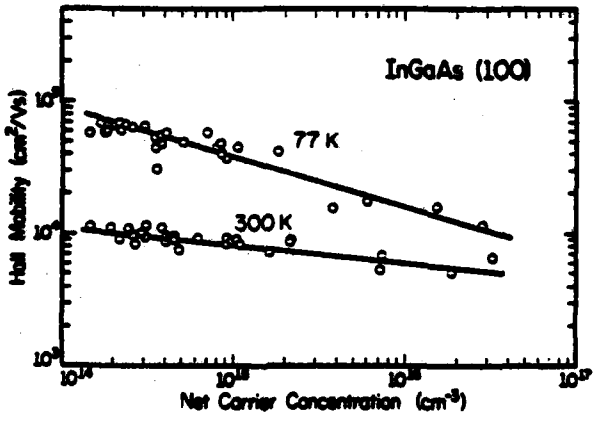


Fig. 2.1 (top left) 77 K mobilities as a function of carrier concentration for VPE Hydride InP plotted with the Rode curves for InP.

Fig. 2.2 (top right) Hall mobility at 77 and 300 K versus N_D-N_A of the InP layers grown in this work. The solid curves show Rode's calculation of μ_{77} for two compensation ratios.

Fig. 2.3 (bottom) Hall mobility at 77 and 300 K versus N_D-N_A of the InGaAs layers grown in this work.

Table 2.1

HIGH PURITY VPE InP HALL DATA

	Carrier Conc.(cm^{-3})		Mobility (cm^2/v-sec)		Total Flow (cm^3/min)	Growth Rate (μm/min)
	η_{77K}	η_{300K}	μ_{77K}	η_{300K}		
VPE I 221	5.2×10^{14}	6.7×10^{14}	71,000	3270	250	0.6
VPE I 220	3.5×10^{14}	4.2×10^{14}	60,000	3400	250	0.4
VPE I 219	5.8×10^{14}	7.8×10^{14}	51,000	3590	500	2.0
VPE I 216	4.8×10^{14}	6.2×10^{14}	57,500	3800	750	2.0
VPE I 206	1.0×10^{15}	1.4×10^{15}	53,000	3400	1250	2.3
VPE I 205	5.2×10^{14}	5.7×10^{14}	54,000	4330	1250	2.6
VPE I 170	5.7×10^{14}	6.4×10^{14}	51,500	3700	933	1.7
VPE I 79	7.9×10^{14}	1.2×10^{15}	54,000	3110	1510	1.6
VPE I 76	5.9×10^{14}	1.3×10^{15}	57,500	3600	1510	1.6
VPE I 48	1.9×10^{14}	1.5×10^{14}	60,000	2920	1040	0.2
17-1*						
Fairman et al, KV-440*	1.3×10^{14}	1.2×10^{14}	140,000	6060		
Fairhurst et al.	1.2×10^{14}	2.2×10^{14}	120,000	5156	~2500	

* Best reported VPE Material (both Halide)

a sample grown by the hydride technique. It is somewhat more compensated than high purity material grown by LPE and the 300 K mobility is not as large as one would expect for a layer with such high 77 K mobility. Some samples, for example VPE I-205, with lower 77 K mobility have larger 300 K mobility.

One interesting aspect of the data is the existence of an aging effect first reported by Eastman in InP grown by LPE [R2]. The aging phenomenon in which the 77 K mobility in n-type samples increases and 77 K carrier concentration simultaneously decreases after 3 to 4 months storage at 300 K, was attributed by Eastman to silicon donors changing from shallow to deep states. The Hall mobilities and carrier concentrations of InP grown by the hydride technique changed similarly when stored at room temperature (see Table 2.2). Dramatic increases have been observed in as short a time as one week in which the 77 K mobility changed from 56,800 $cm^2/V\text{-}sec$ to 70,030 $cm^2/V\text{-}sec$. The greatest overall change occurs in the material which starts out with the highest mobility. In the course of 3 months the 77 K mobility of VPE I-221 increased from 71,260 $cm^2/V\text{-}sec$ to 95,920 $cm^2/V\text{-}sec$. The process can be accelerated by annealing at 105°C. The original 77 K mobility and carrier concentration are re-established when the sample is heated to temperatures as low as 400°C (used for alloying contacts). All values for mobility and carrier concentration quoted above were taken immediately after the contacts were alloyed except where otherwise noted.

2.3 LPE Growth of InP and InGaAsP*

Methods for obtaining high-purity InP and InGaAsP alloy epitaxial layers on (100)-oriented InP substrates using liquid phase epitaxy have been explored. The 300 and 77 K electron mobilities for InP and InGaAs are summarized in Figs. 2.2 and 2.3. All of the undoped layers were n-type, and the InP liquid nitrogen mobilities, when compared with the theoretical curves by Rode [R1] for varying compensation, show relatively little compensation. The freeze-out ratios, N_D-N_A (300 K)/N_D-N_A (77 K), of the InP and InGaAs

* This work was supported by the National Science Foundation under contracts NSF ECS-79-17581 and NSF DMR-80-20250-73, the Naval Research Laboratory under contracts N00173-78-C-0129 and N00172-79-C-0184, and the Joint Services Electronics Program (U.S. Army, U.S. Navy and U.S. Air Force) under contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

Table 2.2

Aging Effect in High Purity InP

SAMPLE	VPE I-246		VPE I-221		
	after alloying	after 1 week	after alloying	after 1 month	after 3 months
300K carrier concentration (cm^{-3})	1.32×10^{15}	1.1×10^{15}	6.68×10^{14}	3.85×10^{14}	2.61×10^{14}
77K carrier concentration (cm^{-3}	8.23×10^{14}	7.0×10^{14}	5.16×10^{14}	2.64×10^{14}	1.91×10^{14}
300K Hall mobility (cm^2/V-sec)	2820	2890	3270	3400	3650
77K Hall mobility (cm^2/V-sec)	56,820	70,830	71,260	91,600	95,850

layers are generally between 1.0 and 1.2. The mobilities of these InGaAs layers grown on (100) InP are in fair agreement with the mobilities of InGaAs layers grown on (111)B InP by Oliver [R3] with the exception that for equally high liquid nitrogen mobilities the room temperature mobilities of these layers are lower. Oliver's highest room temperature mobility was 13,000 $cm^2V^{-1}s^{-1}$ and in this work the highest is 11,000 $cm^2V^{-1}s^{-1}$. The InGaAs layers with N_D-N_A for (2-4) x 10^{14} cm^{-3} and liquid nitrogen mobilities above 60,000 $cm^2V^{-1}s^{-1}$ were grown at 687.5°C, and the rest were grown at 627.5°C. In general, the growth of InP and InGaAs above 650°C has resulted in higher purity, probably due to a lower distribution coefficent for silicon at higher growth temperatures. The InGaAs layers with N_D-N_A approximately equal to 1 x 10^{16} cm^{-3} were grown from unbaked solutions and those with $N_D-N_A > 1 \times 10^{16}$ were doped with tin. Typically, InP layers grown from unbaked solutions yielded doping levels closer to 1 x 10^{17} cm^{-3} presumably due to the use of lower quality InP source material.

The ability to obtain high purity layers has been highly reproducible. At the present time 11 of the last 13 InP layers grown using this technique have had liquid nitrogen mobilities between 50,000 and 70,000 $cm^2V^{-1}s^{-1}$ with N_D-N_A between 9.0 x 10^{14} and 2.5 x 10^{15} cm^{-3}. Also, 12 out of the 14 InGaAs layers grown at 687.5°C have had liquid nitrogen mobilities between 55,000 and 70,000 $cm^2V^{-1}s^{-1}$ with N_D-N_A between 1.5 and 4.5 x 10^{14} cm^{-3}. Fewer $In_{0.83}Ga_{0.17}As_{0.40}P_{0.60}$ (λ = 1.15 μm) layers were prepared for van der Pauw measurements, but of those which were measured, the highest purity layer was determined to have N_D-N_A = 5.6 x 10^{14} cm^{-3} with room temperature and liquid nitrogen temperature mobilities of 4,600 and 24,800 $cm^2V^{-1}s^{-1}$, respectively. Most of these layers were grown between runs where device structures were grown which included layers doped with either zinc or tin on InP substrates doped with either zinc or tin. Thus, these results are highly reproducible and the use of dopants in the boat has not had an adverse effect on the purity of layers grown in subsequent runs.

2.4 Photoluminescence Measurements of Shallow Acceptors*

Variable temperature (1.6 - 20 K), high resolution (0.2 Å) photoluminescence measurements were performed on high-purity undoped InP layers grown at 650°C using a III:V gas ratio of one and an HCl partial pressure of 0.02. The exciton region of a highly compensated sample is shown in Fig. 2.4a. The sharp line structure is typical of high-quality InP and includes lines produced by the recombination of free excitons (FE), neutral donor-bound excitons (D^0,X), ionized donor-bound excitons (D^+,X), and neutral acceptor-bound excitons (A^0,X). At high excitation intensity, the band-to-acceptor region of this sample (Fig. 2.4b) shows the "two-hole" (TH) replica of the (A^0,X) doublet for Zn acceptors superimposed on the broader emission bands due to Zn. A donor-to-acceptor peak involving an unidentified (21 meV) shallow acceptor and a sharp line due to an exciton bound to a deep center are also observed.

At low excitation intensity, measurements of the band-to-acceptor region of the sample I-221 (see Table 1.1) as a function of temperature permit the identification of the donor-to-acceptor (D^0-A^0) and conduction band-to-acceptor (e-A^0) peaks involving two different acceptors of different ionization energies. (See Fig. 2.4c). The (D^0-A^0) peaks diminish in intensity relative to the (e-A^0) peaks as the temperature is increased, due to thermal ionization of the donors. This trend permits proper identification of the various peaks when they overlap, as in the present case. The ionization energies of the two acceptors are 45.4 and 40.5 meV, which are those for Zn and the so-called "A_1" acceptor (which may be C or Mg), respectively.

The deep region of the spectrum (Fig. 2.4d) shows a series of sharp lines which are various LO and TO- phonon replicas of the FE emission, superimposed on a broad, structured emission of unknown origin which has not peviously been reported. Future work will be directed toward the identification of some of the unknown spectral features discussed here.

---

* This work was supported by the Army Research Office under contract DAAG-29-82-K-0059, the National Science Foundation under contract NSF DMR-80-20250-73, and the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

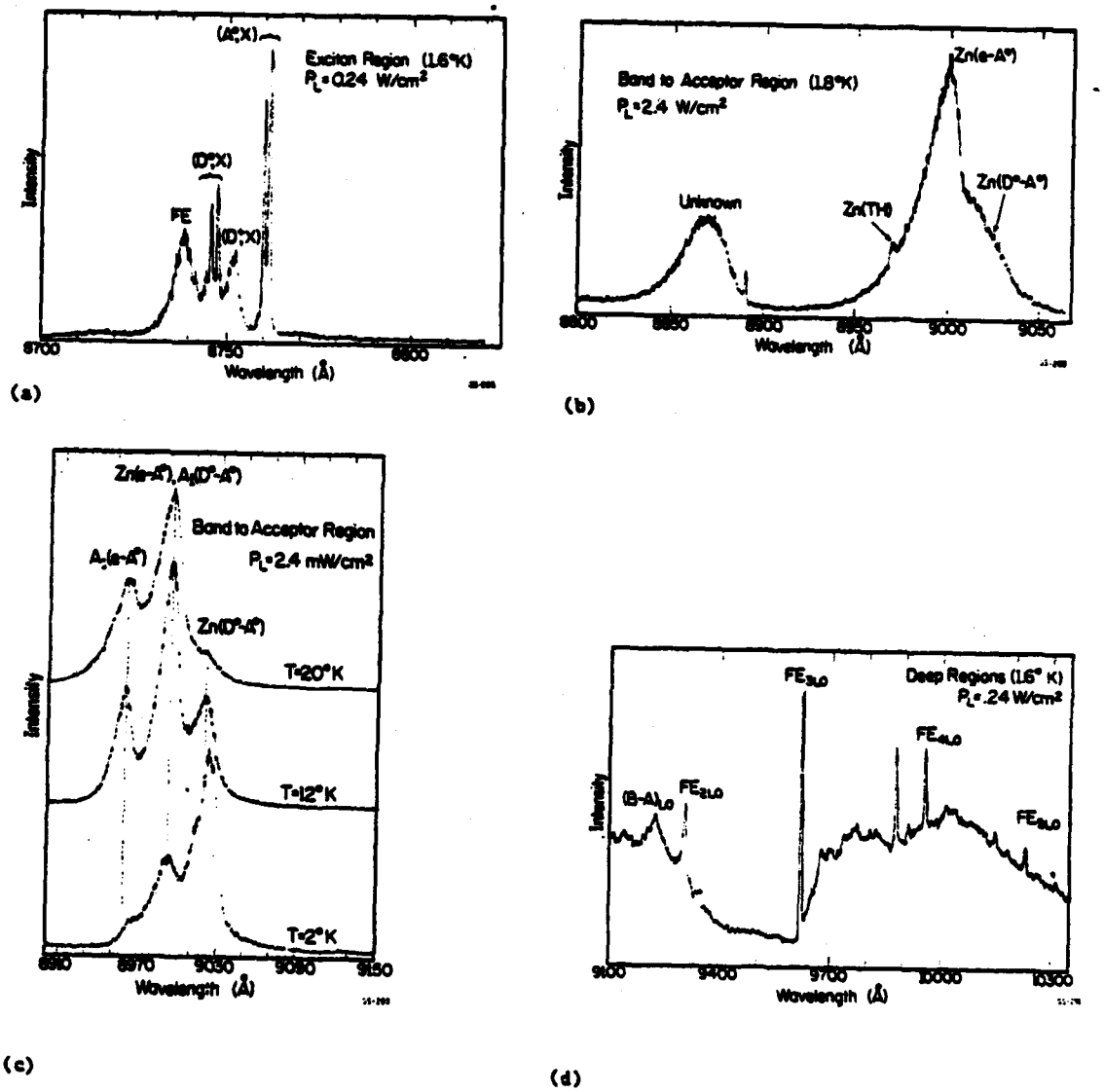


Fig. 2.4 (a) Exciton region of the photoluminescence spectrum of a highly compensated InP sample ($N_{300} = 6.2 \cdot 10^{14} cm^{-3}$, frozen out at 77 K. (b) Band-to-acceptor region of this sample at high excitation intensity. (c) Band-to-acceptor region of sample I-221 at three different temperatures. (d) Deep regions of a high-purity n-type sample.

2.5 Fourier Transform Spectroscopy of Shallow Donors*

The mechanism for the process of photothermal ionization, represented schematically in Fig. 2.5, can be understood by considering an electron initially occupying a donor ground state. The temperature of the sample is 4.2 K so that few electrons are in the conduction band. Absorption of a far infrared photon of appropriate energy can induce a transition to one of the donor excited states, from which the still bound electron may be excited to the conduction band by absorption of phonon(s), contributing to the electrical conductivity of the sample. A photothermal ionization spectrum then consists of a plot of photoconductive response versus photon energy or wavenumber, and contains peaks at the various donor transition energies.

The ground state energies of shallow donors in InP are very nearly hydrogenic but the energy of the donor ground state energy differs slightly from the value predicted from hydrogenic theory, and since this difference is donor species dependent, each hydrogenic transition in a photothermal ionization spectrum contain several closely spaced peaks. Each peak corresponds to a particular donor species present, and has an amplitude which is a measure of the relative concentration of the donor species. The multiplet structure is most easily resolved at high magnetic fields (about 3 T) in the hydrogenic 1s-2p ($m = -1$) transitions. For this reason, the spectra which appear in this paper show only these transitions. The photothermal ionization spectra of Fig. 2.6 show the donor peaks present in high purity VPE and LPE InP grown in our laboratory. The LPE samples typically show three donor peaks labeled A, B, and C. The amplitudes of these peaks are related to the relative concentrations of the associated donors. For example the photoresponse of the sample at the energy of peak B is largely due to the Stark broadened low energy tail of peak C. By numerically fitting a sum of individual peaks of the characteristic shape with adjustable amplitudes to the spectra, it was possible to determine the typical relative concentrations of donors A, B, and C in LPE samples as approximately 0.2 to 0.1 to 0.7. The spectra for the VPE samples show only the peaks A and C in the very different

* This work was supported by the Office of Naval Research under contract N00173-C-0184 (Navy Subc. 81-16 from Washington University) and the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contracts DAAG-29-78-C-0016 and N00014-79-C-0424.

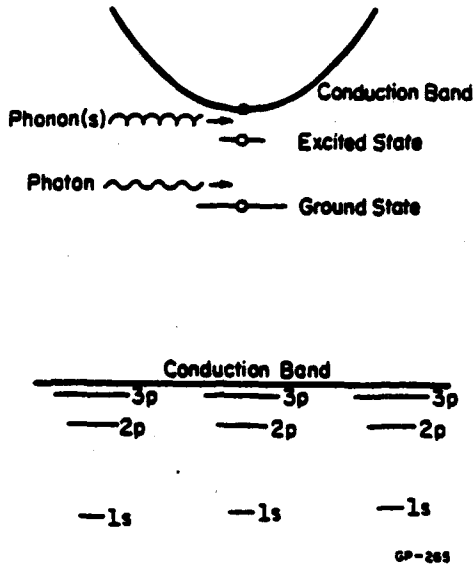


Fig. 2.5 Two representations of the photothermal ionization process:
(a) illustrating the multistep photon-phonon(s) excitation, and
(b) illustrating the difference in ground state (1s) energies for 3 donor species.

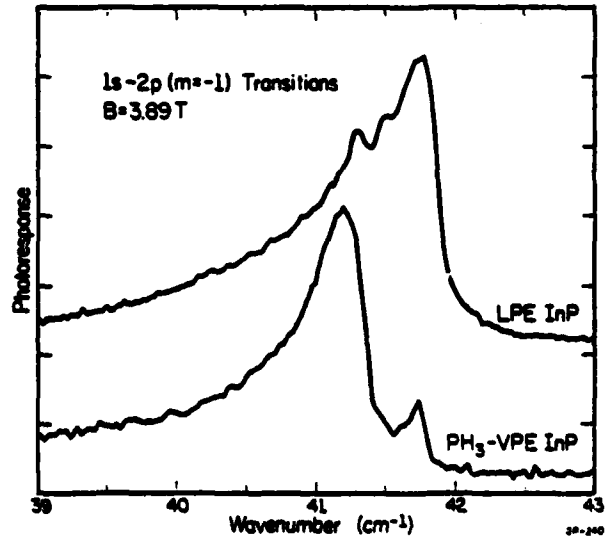


Fig. 2.6 Photothermal ionization spectra for InP grown by LPE and hydride VPE (PH_3-VPE).

relative concentrations of 0.7 to 0.3.

Carefully controlled doping experiments have been performed by several research groups to identify various donor species with the associated photothermal ionization peaks for GaAs. Such experiments are difficult because of the small range of donor concentrations between that of the purest material which can be grown by a given technique and that for which impurity interactions degrade the spectra by broadening and distorting the spectral peaks. Until recently, nearly all InP grown was of insufficient purity to resolve these peaks and so very few donor identification experiments have been performed for InP. Using intentionally doped LPE grown InP, Stradling [R4] has identified photothermal ionization peaks for Sn, Si, and S. This work indicates that the peaks A and C are Si and S, respectively, but these identifications should be regarded as tentative.

REFERENCES

[R1] D. L. Rode, Physical Reviews B, vol. 3, pp. 3287, 1971.

[R2] L. F. Eastman, Proc. of the 1980 NATO Sponsored InP Workshop, p. 117, 1980.

[R3] J. D. Oliver and L. F. Eastman, J. of Electronic Material, vol. 9, p. 693, 1980.

[R4] R. A. Stradling, private communication, 1981.

3. QUANTUM ELECTRONICS

Faculty and Senior Staff

J. G. Eden J. R. Tucker J. T. Verdeyen

Graduate Students

R. Andreatta H. Desai J. Miller
G. Constrini C. Fleddermann J. Osmundsen
K. Greenberg

3.1 Large Density Wave Transport and Dynamics in Quasi-One-Dimensional Conductors*

An ideal one dimensional conductor is a chain of atoms in a linear periodic array. Many linear crystals, such as $NbSe_3$ and TaS_3, approximate this ideal quite closely because the metallic bonds along the axis are strong while the Van der Waals forces between chains are relatively weak. Such one-dimensional metals are unstable to the formation of an energy gap at the Fermi wavevector, k_F, below a critical temperature, T_c (~ 215 K for TaS_3). This causes a superlattice and an associated electron charge density wave (CDW) to form with a wavelength of π/k_F.

Experiments [R1-R5] have shown that charge density waves can move coherently through the lattice in $NbSe_3$ and TaS_3 when the applied electric field exceeds a certain threshold value E_T. John Bardeen developed a model of CDW depinning in which the CDW tunnels coherently through a pinning gap in a manner analogous to Zener tunneling [R6,R7]. In addition he applied photon assisted tunneling theory [R7] to predict the frequency dependent conductivity of $NbSe_3$. Experiments [R8] performed at UCLA have shown excellent quantitative agreement with the tunneling model predictions of the field and frequency dependent conductivities of $NbSe_3$ and TaS_3, except that there seems

This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424 and by the National Science Foundation under grant ECS 81-20038.

to be an additional "classical" component to the a.c. conductivity. However, the results of those experiments have also been interpreted using a purely classical overdamped harmonic oscillator model.

The principal aim of this work is to perform an experiment for which the tunneling and classical models give qualitatively distinct predictions. In this way we hope to either prove or disprove the tunneling hypothesis. If the tunneling model proves to be basically correct, then materials such as TaS_3 may be useful in radio frequency and microwave applications (e.g., sensitive detectors and mixers).

The experiment performed at UCLA [R8] measuring the d.c. conductivity of $NbSe_3$ in the presence of large a.c. signals was interpreted by our group [3.4] in terms of the tunneling model. The experiment, which had previously been interpreted using a classical model, showed excellent qualitative and reasonable quantitative agreement with Bardeen's tunneling model coupled with photon assisted tunneling theory. Very recently field and frequency dependent rectification measurements on TaS_3 performed by our group have yielded results which qualitatively can easily be explained using the tunneling hypothesis but are difficult, if not impossible, to interpret classically. In the near future we plan to make a quantitative comparison of rectification measurements with tunneling theory predictions for a wide range of bias voltages and frequencies.

3.2 Discharge Annealing*

Studies have continued on the use of a glow discharge in Helium to generate an electron beam for annealing ion-implanted semiconductor samples [3.3]. A new diagnostic tool - laser reflectometry - has been developed to allow accurate determination of silicon sample temperature and regrowth velocity [3.5].

Laser reflectometry consists of directing light from a Helium-Neon laser at 632.8 nm onto a semiconductor sample during annealing. The reflected beam is synchronously detected using a vacuum photodiode and lock-in amplifier to remove background signal due to black body radiation from the sample. As the

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

silicon is heated by the electron beam, its index of refraction increases, increasing the reflectivity of the sample. The relation between index of refraction and temperature for silicon is known [R9], so a relation between temperature and reflectivity can be calculated. Thus, the temperature of a silicon sample can be monitored during annealing.

Reflectometry also provides an accurate measure of the regrowth time during annealing [R10]. The amorphized surface layer has an index of refraction which differs from that of the single-crystal substrate. The discontinuity in refractive index causes a reflection of the laser beam from the amorphous-single crystal interface, which interferes with the light reflected from the sample surface. During regrowth, the interface proceeds to the surface by solid phase epitaxy, causing the path length of the beam reflected from the interface to decrease. Thus, the phase of the beam reflected from the interface continually changes with respect to the phase of the beam reflected from the surface, causing maxima and minima or "interference fringes" in the reflectivity as the sample regrows. Ultimately, the reflectivity reaches the value for single crystal silicon. Using this technique, the regrowth rate was measured as a function of electron beam power and sample temperature. Our results for annealing large area samples show excellent agreement with laser annealed samples [R11], indicating that the discharge anneal system shows promise as an alternative to laser annealing systems.

Studies were also performed on the annealing of single crystal silicon with a polycrystalline silicon layer grown on top. As deposited, the samples had sheet resistivities greater than 200 Ω per square. Our study shows that with the discharge system, these samples can be annealed yielding sheet resistivities of 15 Ω per square and less. These results are obtained over large area samples with anneal times less than five seconds.

3.3 Plasma-assisted Etching*

Recent work in the area of plasma-assisted etching has been directed toward the design and construction of an RF plasma discharge system. Previous

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

research utilized a DC hollow-cathode discharge to generate etching species while the new design employs an inductively coupled RF discharge. This offers several advantages. High frequency discharges generally tend to provide: (1) a higher degree of ionization and dissociation, (2) a high ratio of electron temperature to ion and gas temperatures, and (3) a wider range of operating gas pressures. Furthermore, sputtering effects due to the electrode material are eliminated by the inductively-coupled configuration.

A major improvement in diagnostics is provided by the addition of a quadrupole mass spectrometer. This system features the ability to detect both positive and negative ions. The quadrupole contains its own source of ionization which can be switched off. The system can then be utilized to directly detect species in the plasma along with providing means to analyze downstream products. Currently, the QMS is connected downstream of the discharge-sample region via a variable-leak valve. A further improvement would connect the quadrupole, via a pinhole leak, to the discharge-sample region and would enable the detection of many of the ionic species involved in the etching process.

Much of the work currently being done in this field concerns the "Reactive Ion Etching" scheme. This differs from conventional "plasma etching" in that physical processes as well as chemical are used to remove material. Concern has been raised recently that damage to the semiconductor occurs due to the bombarding ions. Surface states at the SiO_2-Si boundary, for example, are thought to be caused by this. Machines designed to exploit the RIE scheme employ a parallel plate RF discharge whereby the electrode upon which the samples are placed assumes a negative bias proportional to the ratio of the surface area of the electrodes. The system configuration we have constructed avoids this and allows a DC bias to be superimposed on the sample. Therefore, we hope to study the influence of ion bombarding effects on the anisotropy of etch as well as damage to the semiconductor.

Preliminary etching runs have been conducted and etching has been achieved. Further work to determine etch rate versus various parameters of the system are being conducted in an effort to "calibrate" the system with respect to known results in the literature. In particular, attention is focused on observing etch rate versus sample bias in the RF system as compared to the results already obtained in the DC hollow-cathode configuration.

3.4 Laser-Induced Growth of Semiconductor Films*

The objective of this research program is to investigate the chemistry and optical properties of excited atoms and molecular radicals produced by ultraviolet photodissociation and the interaction of these excited species with a surface to generate a thin film. Specifically, an ultraviolet excimer laser is being used to photodissociate inorganic molecules that contain a semiconductor atom (such as SiH_4, GeH_4 or $SiCl_4$). The spectroscopy of these laser-generated plasmas as well as the electrical and chemical properties of the resulting Ge or Si films are under investigation.

Initial experiments involved the photodissociation of SiH_4, $(CH_3)_4Si$ and GeH_4 in the ultraviolet using excimer lasers and succeeded in growing Si and Ge films on amorphous SiO_2 substrates. These experiments were conducted at room temperature and the resulting Ge or Si films were found to be polycrystalline with grain sizes of up to 0.5 μm. However, the films were highly resistive due to intergranular voids formed as a result of the large deposition rates (~ 1 nm - s^{-1}).

In more recent experiments, a CW CO_2 laser has been used in conjunction with the excimer laser to produce films of much higher quality. The CO_2 laser maintains the spatial selectivity of the technique and serves to moderately heat the substrate, thus enhancing the surface mobility of an absorbed semiconductor atom. However, since it is the excimer laser that, by a non-thermal process frees the Ge or Si atom from the parent molecule, the films can be deposited at temperatures at least 100-150°C lower than those required for pyrolytic deposition. For example, Ge films grown at a substrate temperature of 300°C for 10-20 minutes are ~ 1 μm thick and exhibit room temperature mobilities of ~ 100 cm^2-$V^{-1}s^{-1}$. Hall measurements also indicate carrier concentrations of ~ 10^{18} cm^{-3} and x-ray studies using a powder diffractometer show the films to be polycrystalline with no preferred orientation. Substrate temperature measurements show that the excimer laser heats the substrate by 10°C or less. Also, we have demonstrated that (111) Ge can be epitaxially grown on 1$\bar{1}$02 oriented sapphire substrates by pyrolyzing GeH_4. Current experiments are focusing on accomplishing the same goal at

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424 and by the Air Force Office of Scientific Research under contract AFOSR 79-0138.

lower substrate temperatures by photodissociating GeH_4.

Emission from atomic Ge and the germylene (GeH), has also been observed and profiles of fluorescence intensity versus distance from the substrate are being measured. These results will later be incorporated into a computer model of the gas phase/surface kinetics in an effort to better understand the processes involved in the nucleation of Ge films.

REFERENCES

[R1] R. M. Fleming, D. E. Moncton and D. B. McWhan, "X-ray scattering and electric field studies of the sliding mode conductor $NbSe_3$," Physical Review B, vol. 18, no. 10, p. 5560, 1978.

[R2] R. M. Fleming, "Electric-field depinning of charge-density waves in $NbSe_3$," Physical Review B, vol. 22, no. 12, p. 5606, 1980.

[R3] G. Gruner, L. C. Tippie, J. Sany and W. G. Clark, "Frequency-dependent conductivity in $NbSe_3$," Physical Review Letters, vol. 45, no. 11, p. 935, 1980.

[R4] A. H. Thompson, A. Zettl and G. Gruner, "Charge density wave transport in TaS_3," Physical Review Letters, vol. 47, p. 64, 1981.

[R5] A. Zettl and G. Gruner, "Charge density wave dynamics in TaS_3," to be published.

[R6] John Bardeen, "Theory of non-ohmic conduction from charge-density waves in $NbSe_3$," Physical Review Letters, vol. 42, no. 22, p. 1498, 1979.

[R7] John Bardeen, "Tunneling theory of charge-density-wave depinning," Physical Review Letters, vol. 45, no. 24, p. 1978, 1980.

[R8] G. Gruner, W. G. Clark and A. M. Porris, "ac-induced dc conductivity of the CDW state in $NbSe_3$," Physical Review B, vol. 24, no. 6, p. 3641, 1981.

[R9] Y. J. Van der Meulen and N. C. Hien, J. of the Optical Society of America, vol. 64, p. 804, 1974.

[R10] G. L. Olson, S. A. Kokorowski, R. A. McFarlane and L. D. Hess, Applied Physics Letters, vol. 37, no. 11, p. 1019, 1980.

[R11] J. A. Roth, G. L. Olson, S. A. Kokorowski and L. D. Hess, in Proc. of Laser and Electron-Beam Interactions with Solids Symposium of the Materials Research Society, ed. J. F. Gibbons, L. D. Hess and T. W. Sigmon, pp. 413-426, Elsevier North-Holland, 1981.

4. SEMICONDUCTOR PHYSICS

Faculty and Senior Staff

B. G. Streetman
J. P. Leburton
K. Hess

Graduate Students

S. Banerjee	B. Bereznak	B. Lee
P. Gavrilovic	U. Ekenberg	P. Martin
C. T. Hsieh	T. Wang	J. Oberstar
K. Brennan	M. Keever	Y. Tang
S. Chan	C. Lee	R. Tong
R. DeJule		A. Tejayadi

4.1 Introduction

This research involves study of basic properties of semiconductors, methods of device processing, and new device concepts. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance, especially in connection with modulation doping. We are studying ion implantation and annealing of Si and III-V compounds, including laser and electron beam processing. These experimental studies include examination of deep-level impurities and defects arising from implantation and annealing. Several aspects of this work are done in collaboration with other units, particularly the studies of materials grown by molecular beam epitaxy (MBE, Unit 1).

4.2 Laser and Electron Beam Annealing of Semiconductors*

In our studies of the physics and materials problems underlying new device processing techniques, we have examined several effects of transient annealing in semiconductors. While these methods exhibit great promise for more flexible processing of devices, a better understanding of the annealing mechanisms is required for reliable application to fabrication. In the previous reporting period we described extensive experiments in pulsed laser annealing of silicon. During this period we have published results of that work applied to BF_2^+ amorphized Si. We have also examined electrical activation and residual defects (using DLTS) in amorphized Si recrystallized by swept line electron beam annealing. We have also presented results of a new electron beam annealing approach in which electrons are derived from a plasma discharge.

Considerable work has been done on recrystallization of deposited silicon on SiO_2 using lateral seeding from windows in the oxide to underlying crystalline Si. The approach used is heating by a narrow carbon strip which traverses the sample surface in a swept line pattern. Large single crystals have been obtained by this method, but these crystals contain low-angle grain boundaries. Studies are underway on the crystallographic and electrical properties of these films.

4.3 Implantation and Annealing of Compound Semiconductors**

In the last reporting period we described studies of encapsulation and annealing in InP. Based upon those results, we have carried out extensive measurements of impurity migration in implanted InP. We find that implanted impurities (e.g., Be) undergo anomalous migration during annealing of the damage, and also that compensating impurities (Fe, Cr) used to make semi-insulating InP migrate considerably. Correlations were observed between the

---

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424, by the Army Research Office under Contract DAAG 29-80-C-0011, and by the Office of Naval Research under Contract N00014-81-K-0431.

** This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424, and by the Office of Naval Research under Contract N00014-76-C-0806.

migration of implanted Be and either Fe or Cr. After annealing, flat tails of Be extending over several microns have been observed, with an accompanying decrease in Fe or Cr over the same regions. Similar flat tails were observed in the case of implanted Mg. The migration of implanted Si in InP is much less pronounced; however, Fe redistribution is observed which can seriously affect the electrical properties of Si implanted layers.

Studies of anomalous impurity migration have also been initiated in GaAs. Preliminary results indicate that implanted S in GaAs diffuses much less during annealing when Si is present. However, this effect is pronounced only at relatively low S doses. At higher S concentrations, the deep migration commonly observed is not impeded by Si co-implantation. Work is currently underway with GaAs layers doped with Si during growth, to separate out the effects of defects and chemical effects between the impurities.

4.4 Electronic Transport at High Energies*

The goal of this research has been to develop a complete theory of transport phenomena at high energies (> 1 eV above the conduction band edge) in bulk semiconductors. In previous years we have developed a Monte Carlo simulation which included a realistic band structure as calculated by the empirical pseudopotential method. The scattering rates were essentially computed by the Golden Rule with the deformation potential constants regarded as adjustable parameters. From the fit to a large number of experimental results (impact ionization rate, saturation velocity, effects such as electron collection in double-heterojunctions and real space transfer) we have obtained a reliable set of coupling constants. The scattering rates are proportional to the square of the coupling constants and the final density of states. Because of the peaks in the density of states there are regions in the bands exhibiting extremely high scattering rates. These high rates make it desirable to use a more rigorous approach than the use of the Golden Rule to include, e.g., collision broadening effects. Therefore we calculated the self energy Σ from the relation (see e.g. J. M. Ziman, Elements of Advanced Quantum Theory, Cambridge Univ. Press 1969).

---

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy and U.S. Air Force) under contract N00014-79-C-0424 and by the Office of Naval Research under contract N00014-76-C-0806.

$$\Sigma = \iint \frac{F^2}{\omega^2 - \omega_q^2 + i\delta} \frac{1}{E(k) - \omega - E(k-q) + \Sigma} \, dq \, d\omega$$

from Σ the scattering crossection is obtained via the optical theorem. Fig. 1 shows 2 Im as well as the scattering rate as calculated by the Golden Rule (G). To lowest order the two curves should be identical. Notice the deviation between the curves at high energies. We have meanwhile performed calculations of the impact ionization rate including these effects. The qualitative features of the theory of impact ionization remain the same; there are, however, quantitative differences. These become especially important at large energies and will influence significantly processes such as the emission of electrons from silicon into silicon dioxide which is so important for stability considerations of micron and submicron devices. Detailed computations are in progress.

4.5 Transport in Layered Heterojunction Structures*

We have investigated the possibility of storage and switching between the layers of GaAs separated by $Al_xGa_{1-x}As$ layers. The test structure shown in Fig. 2 was fabricated using standard photolithographic and chemical etching techniques. Four ohmic contacts were formed by vacuum evaporation of Au-Sn and subsequent alloying at 450° for 30 sec in flowing H_2. The resulting structure had a dumbbell-shaped center region containing all nine heterostructure periods, each of which was contacted at each end by an ohmic contact (labelled side contact in Fig. 2) that was diffused down through most of the layers. The areas containing the main contacts (see Fig. 2) were etched down so that the top three GaAs-$Al_xGa_{1-x}As$ layer pairs were removed, leaving only the lower six periods contacted by the main contacts. If voltages are applied only to the main contacts (no applied voltage on side contacts) then only the GaAs layers in the bottom six periods will have high electric fields. Some of the electrons that escape from the GaAs layers in these bottom six periods can propagate into the upper electrically isolated layers nearer the surface in the dumbbell bridge. If the sample is cooled to cryogenic temperatures, the electrons that lose energy in these isolated

* This work was supported by the Office of Naval Research under contract N00014-76-C-0806 and the Army Research Office under contract DAAG29-80-C-0011.

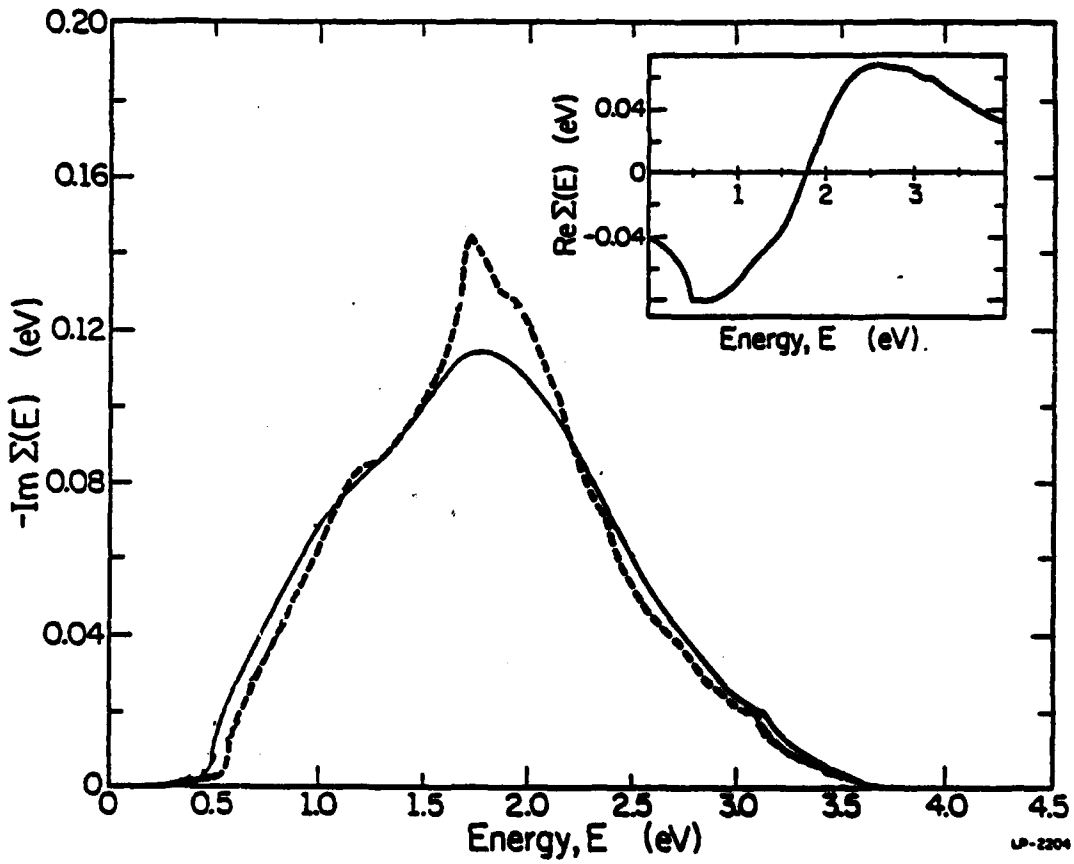


Figure 4.1 Imaginary and real (inset) part of the self energy as calculated in the Fock approximation (full line) and the Golden-rule result (dashed line) for the conduction band of GaAs. For weak coupling the two curves should be identical.

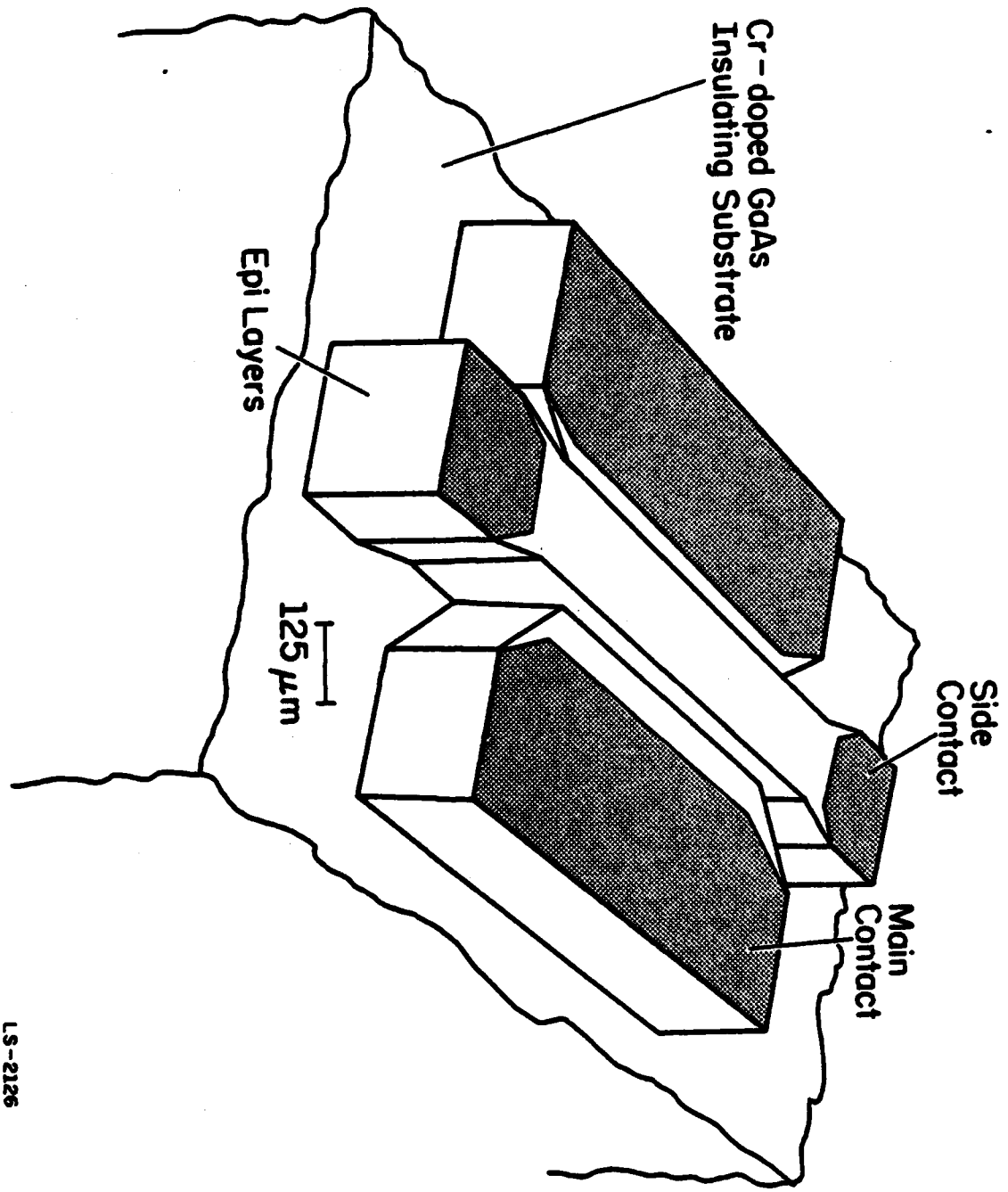


Figure 4.2 Device structure used for measuring switching and storage effects. When a high electric field is applied hot electrons can propagate from the bottom high field layers to the upper electrically isolated layers.

layers will become trapped in the GaAs regions and will not be able to gain enough energy from the crystal lattice or fringing low electric fields to escape by thermionic emission. Thus, as soon as the electric field between the main contacts becomes high enough to cause electrons to be emitted from the lower GaAs layers, a fraction of these electrons can propagate to the upper isolated GaAs layers where they are trapped, provided that the side contacts do not connect through to the lower layers interconnected by the main contacts. The resulting current between the main contacts will be reduced for all following measurements of the current at lower fields. Suppose a voltage is then applied only to the side contacts so that the resulting electric field in the dumbbell bridge region is high enough to allow thermionic emission of the electrons in all the upper GaAs layers as well as those between the main contacts. The initially higher concentration of electrons stored in the top three periods will then be redistributed to the other periods, thus restoring the original carrier distribution of the sample before any voltages were applied. The current-field characteristics between the main contacts at low fields will then also return to their original values.

The results of current-field measurements between the main contacts on a sample cooled to 10 K is shown in Fig. 3. Measurements were performed using 700 ns voltage pulses at low repetition rates to reduce sample heating. Measurements of the current vs. field shown in the graphs were taken at 600 ns after the beginning of each pulse, although no time dependence was observed in the pulses between 1 and 700 ns. The sample was mounted on a temperature controlled cold finger in an evacuated sample chamber and standard 50-Ω sampling oscilloscope and x-y recorder techniques were used. All measurements were performed with the sample in the dark. The upper solid line in Fig. 3 shows the virgin current-field characteristics between the main contacts when the first voltage was initially applied to the main contacts (no voltage between side contacts). After the electric field exceeded a threshold value necessary to cause a real-space transfer of electrons, the voltage was returned smoothly to zero, resulting in the lower solid curve.

The significantly lower current values measured as the voltage was returned to zero indicates that a fraction of the electrons have been transferred and stored and can no longer contribute to the current. Repeating the same voltage scan several seconds later (dashed curve in Fig. 3) revealed

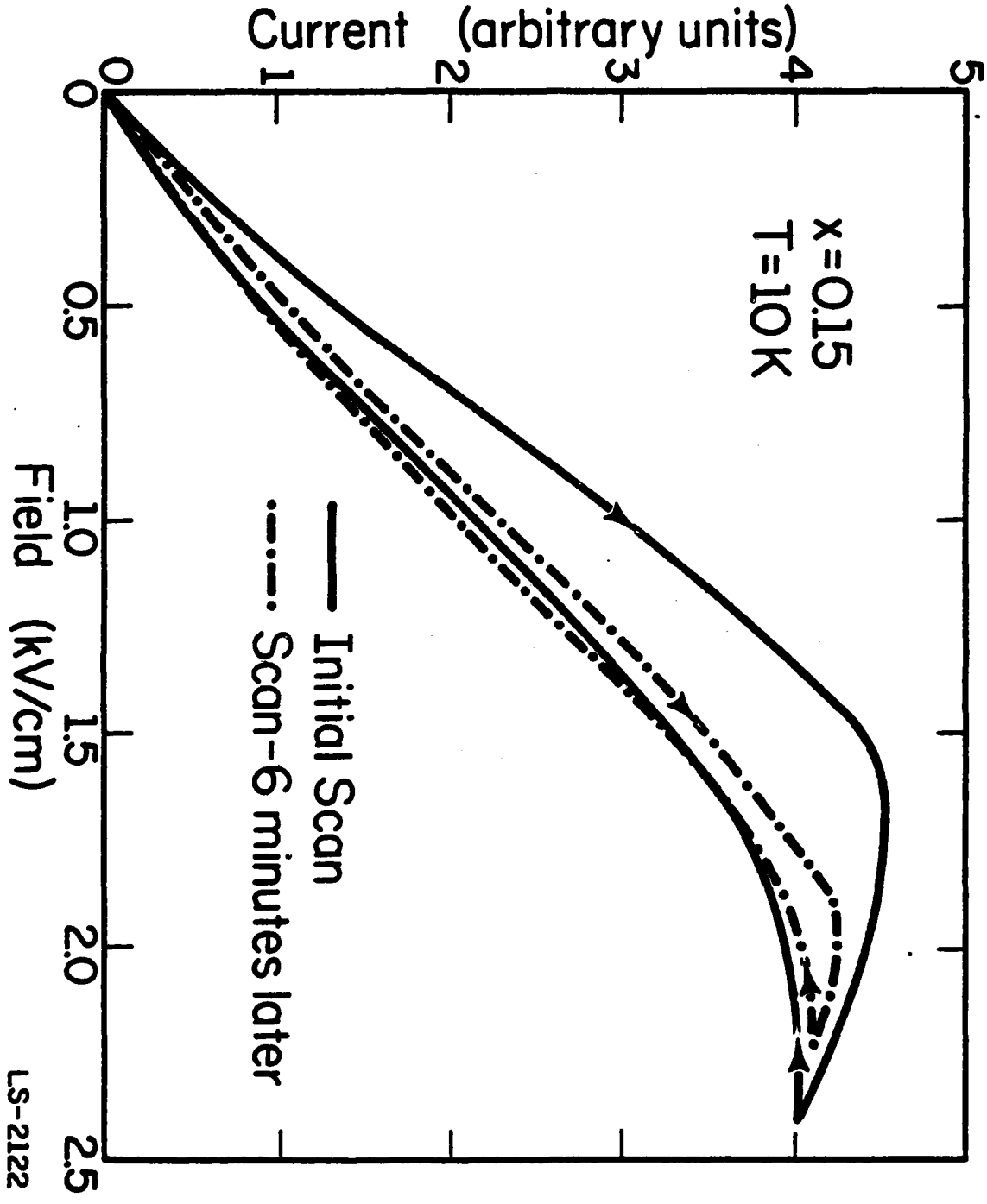


Figure 4.3 Current-field characteristics measured between the main contacts (Fig. 4.2) at T_2 = 10K. The prolonged reduction in the current flow following the initial voltage scan is due to the switching and storage of electrons. The initial (virgin) scan characteristics are restored by applying a high electric field between the side contacts.

only a slight change in the reduced current. Another scan of the voltage several minutes later (dot-dashed curve) exhibited only a small further increase in the reduced current, indicating the number of stored electrons had changed very little. Immediately thereafter, a high field was applied between the side contacts (no applied voltage on main contacts) to redistribute the stored electrons. The following voltage scan between the main contacts resulted in a retracing of the initial virgin solid line current-field curve. The above pattern of voltage applications was repeated many times with the same results. The experiments are still inconclusive as to whether the electrons are stored in the upper GaAs layers or in deep traps in the $Al_xGa_{1-x}As$ or in surface states, since a complete electrical separation of the layers (side contacts) is difficult to achieve. Also, the density of deep traps is not well-known in these samples and more research needs to be done. However, the effect not only proves the concepts of real space transfer as discussed before, but also shows the device potential. In addition, interesting physical parameters may be determined by time resolved measurements of the kind described above, since all these effects are extremely sensitive to electron-phonon interaction, quantum mechanical transmission coefficients, etc.

4.6 Ballistic Transport and Ultrafast Submicron Devices*

We have used our Monte Carlo simulation program to investigate the possibility of ultrafast collision free transport as proposed by Eastman at Cornell. The result of our simulation is that in a narrow range of parameters ultrahigh speeds are possible. Collectors and drain regions of current semiconductor devices, however, are outside this parameter range (because of the high voltage drops) and therefore represent the bottleneck for speed. This problem is fundamental in nature and can only be circumvented by constructing devices with extremely short collector or drain regions. Fig. 4 shows typical results of transit times vs device length for GaAs with the electric field as parameter. The electrons are assumed to be injected at 300 meV energy and transverse the distance indicated at the x-axis. Notice the paradoxical increase in transit time with increasing field, which is caused by the population of higher conduction band minima.

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424 and the Army Research Office under contract DAAG29-80-K-0069.

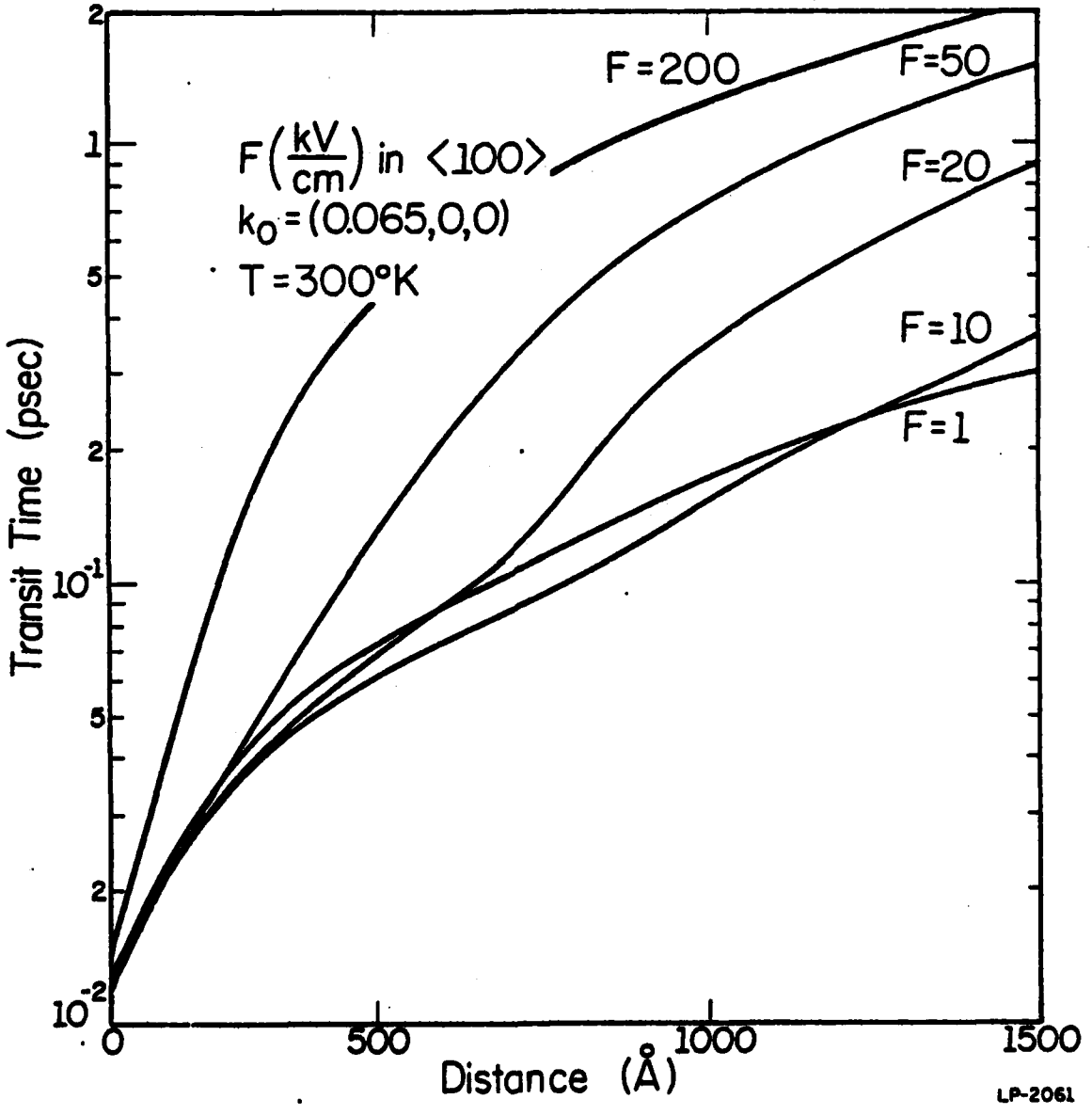


Figure 4.4 Transit time of electrons versus the device length with the electric field as a parameter for T = 300 K.

5. THIN FILM PHYSICS*

Faculty and Senior Staff

J. E. Greene

G. Bajor

Graduate Students

U. Alpay
S. A. Barnett
S. Fang
S. Gorbatkin
R. E. Klinger
B. Kramer
D. Lubben
M. A. Ray
L. Rivaud
A. Rockett
L. Romano
I. Shah

5.1 Semiconductor Crystal Growth from the Vapor Phase: Ion-Surface, Plasma, and Laser Stimulated Reactions

We are studying energetic particle-surface interactions and stimulated gas phase reactions which control the nucleation and growth kinetics, chemistry, and physical properties of compound and alloy semiconductors grown from the vapor phase by UHV ion beam sputtering, plasma-assisted chemical vapor deposition, accelerated beam MBE, and laser-induced chemical vapor deposition. The common feature of these techniques is that crystal growth proceeds under non-equilibrium thermodynamic conditions through the production of highly reactive gas phase species: excited atoms, metastables, radicals, and ions. Such species transfer energy to the growth surface upon condensation thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing film growth at lower temperatures, a wider range in controlling doping concentrations and tailoring film properties, and the growth of unique metastable materials. This work is being pursued from both an analytical and an experimental point of view to establish a detailed understanding of fundamental film growth mechanisms. We have recently published two invited review papers in this area [5.3, 5.4]. Results from

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy and U.S. Air Force) under contract N00014-79-C-0424.

this research have a wide range of applications in addition to crystal growth including the active research fields of reactive ion etching, ion beam lithography, microchemical analysis, plasma chemistry, and laser–materials interactions.

5.2 Ion/Surface Interactions

We have developed general models for predicting elemental incorporation probabilities of accelerated species incident upon growing film surfaces during vapor phase deposition [5.4]. Trapping (low energy implantation), scattering, re-evaporation, and preferential sputtering are accounted for. More recently we have added terms for collisional mixing and segregation of dopants. As discussed briefly below, the use of these models in analyzing experimental data not only leads to a more detailed understanding of film growth processes but also gives predictive capability in designing new experiments or considering the growth of new materials.

5.2.1 Nucleation and Growth Kinetics

Initial experiments using both in-situ electron diffraction and replication transmission electron microscopy have been carried out to investigate the effect of low energy (< 200 eV) ion bombardment on nucleation kinetics. Preliminary results for Ge and GaAs on amorphous SiO_2 substrates show more than an order of magnitude increase in grain size as well as a large increase in the degree of preferred orientation, (100) and (110), respectively.

Ion/surface interaction effects have been found to greatly affect the growth kinetics of sputter deposited single crystal GaAs. Experiments were carried out on (100) GaAs substrates as a function of deposition rate R, growth temperature T_s, incident As/Ga flux ratio J_{As}/J_{Ga}, and ion acceleration voltage V_s. Atomic Ga and As beams were obtained by sputtering from a single crystal undoped GaAs wafer while the simultaneous evaporation of arsenic from an effusion cell provided an As_4 overpressure. The results show that in direct contradistinction to MBE growth using thermal beams, R depends not just on J_{Ga} but also on the surface composition of the growing film and, hence, on T_s and the relative As_4 overpressure. This is primarily due to secondary

sputtering effects. An analysis of the data based upon earlier studies involving the reaction of thermal molecular As_2 and As_4 on heated GaAs surfaces allows a determination of the surface binding energy of Ga as a function of the As surface coverage.

5.2.2 Elemental Incorporation Probabilities

Achievable doping concentrations of many important dopants in MBE films grown under practical conditions has been limited by low thermodynamic sticking probabilities. However, acceleration of these dopants to relatively low energies, a few hundred eV, has been shown by several investigators to result in enhancements in net incorporation probabilities in GaAs and Si of up to eight orders of magnitude. We reported similar effects for S doping of sputter deposited GaAs last year.

Using the model described briefly in section 5.2 above, we have analyzed our experimental results for accelerated S doping of sputter deposited GaAs [5.5] and As doping of MBE Si (grown by Dr. Ota, Bell Laboratory, Holmdale). In both cases, several orders of magnitude increases were observed in the overall incorporation probability, however the detailed mechanisms involved were quite different. In the former case, S concentrations [S] of up to 1.2 x 10^{21} cm^3, as measured by secondary ion mass spectrometry, were obtained using an H_2S/Ar glow discharge source. The primary mechanisms of incorporation involved a competition between dissociative chemisorption coupled with trapping and preferential secondary sputtering giving rise to a minimum in [S] at a critical substrate potential. [S] increased linearly with increasing H_2S partial pressure but was not affected by varying the As/Ga flux ratio between 12 and 40. Very sharp doping profiles (see also section 5.2.3) with no indication of surface segregation were obtained for programmed doping steps. In the Si:As case, the total ion current was low enough to neglect sputtering, but enhanced near-surface diffusion and segregation as well as trapping had to be considered.

While the growth parameters were very different in the above experiments, the calculated results agreed very well with measured results in both cases. The model is now being used to make predictions in other systems and to provide a general basis for understanding accelerated doping.

5.2.3 Segregation and Dopant Distribution

A segregation model was developed for predicting surface accumulation of dopants and the corresponding dopant depletion region near the film/substrate interface during MBE and sputter deposition. The model does not require a rate-kinetic limitation to lattice incorporation but instead is based on a surface segregation potential controlled by the strain free energy resulting from misfit solute atoms, "bond breaking" terms due to a decrease in the surface free energy when bulk species with lower enthalpies of sublimation are exchanged with surface atom species, and the excess entropy of mixing. The depth distribution of dopant throughout the entire film can be calculated by solving the full position and time dependent second law of diffusion accounting for both diffusional and drift fluxes. The segregation potential enters into the latter term through the drift velocity. The equations are solved in differential difference form subject to boundary conditions depending on the nature of the experiment.

As a first application of the model [5.10], we applied it to the well known problem of Sn surface accumulation in MBE grown GaAs where the surface concentration Θ_{Sn} is typically 3 to 4 orders of magnitude greater than that of the bulk C_{Sn} and a Sn deficient region up to 100 nm wide is left at the film/substrate interface under normal growth conditions. Calculated Sn profiles were found to agree extremely well with measured profiles, obtained using secondary ion mass spectrometry (SIMS) in several series of GaAs:Sn samples (grown in collaboration with Prof. Morkoç) where the growth temperature, the As_4/Ga flux ratio, and the Sn flux was varied. By adding terms accounting for trapping and collisional mixing (recoil implantation) we can also model accelerated beam doping experiments and are now applying the model to interpret and explain published results for accelerated doping of MBE-grown Si. Finally, the model can also be used to predict experimental conditions leading to better control over dopant distributions. Using these ideas, we have demonstrated a reduction of Θ_{Sn} in GaAs by ~ two orders of magnitude with a correspondingly sharper profile at the film/substrate interface for the same C_{Sn} used in the above experiments.

5.2.4 Growth of Single Crystal Metastable Semiconductors

As reported last year, we are carrying out the first detailed study of the growth and physical properties of new single crystal metastable semiconductors. The key feature in stabilizing the growth of these materials is the controlled use of low energy ion bombardment during deposition to modify elemental sticking probabilities and adatom diffusivities and to promote collisional mixing. The research described in sections 5.1 through 5.2.3 above has provided a much better understanding of the growth of these unique materials. During the past year we have concentrated our efforts on the study of $(GaAs)_{1-x}Ge_x$ because of the importance of the end-members, the interest in Ge/GaAs heterostructures, and the fact that it is representative of a new subclass of potentially important alloys, $(III\text{-}V)_{1-x}IV_x$.

Epitaxial metastable $(GaAs)_{1-x}Ge_x$ alloys with compositions ranging from x = 0 to x = 1 have been grown on (100) GaAs substrates by ion beam sputtering in an ultrahigh vacuum system. Electron channeling, double crystal X-ray diffractometry, and X-ray t[illegible]graphy analyses indicate that the films are of very high crystalline perfection. Either n-type or p-type conduction, with n and p varying over several orders of magnitude, could be obtained by varying the film composition, the growth temperature, and the As overpressure during deposition. The equilibrium GaAs-Ge pseudobinary phase diagram has been determined by differential thermal analysis to be a simple eutectic with an invariant temperature and composition of 880°C and ~ 18 mole % GaAs. A great deal of insight into the bonding structure of these alloys has been achieved by fitting calculated liquidus, solidus, and soluns boundaries, based on pairwise potential quasi-chemical models, to the experimental results. Such models inherently contain not only free energy (i.e. activity) vs x data but also require knowledge of nearest-neighbor bonding configurations.

Collaborations established with Prof. Dow (theory), Prof. Raccah at UICC (Raman), and Dr. Aspnes at Bell Laboratory, Murray Hill (spectroscopic ellipsometry) have also provided a more quantitative understanding of these alloys. Raman data show single mode behavior across the alloy system with the LO mode obeying a Vegard's law type of behavior while the TO mode frequency increased approximately linearly up to x = 0.75 and then much more rapidly thereafter. The elemental mass differences were too small to give rise to localized modes but strong alloy broadening was observed. The broadening

effects correlate with disorder along the (111) bonding direction. Optical absorption measurements indicated a large negative bowing in the direct E_o band gap as a function of alloy composition. However the shape of the bowing can not be fitted by simple dielectric parabolic models. Ellipsometric data also indicate large negative bowing in the direct E_1 and E_2 transitions.

Very recent measurements using analytical scanning transmission electron microscopy combined with energy dispersive X-ray spectroscopy indicate that the alloys are homogeneous to within the 3 to 5 nm resolution of the techniques while phase separation was observed after annealing near 800°C. This technique offers potential for in-situ phase transformation studies as well as for resolving current arguments concerning clustering in superlattices.

5.2.5 Reactive Ion Etching of GaAs

The first detailed study of the reactive ion etching (RIE) of GaAs has been carried out by our group [5.8]. We investigated the RIE of (100) GaAs in pure CCl_2F_2 and CF_4 discharges as well as in mixtures of Ar and CCl_4, CCl_2F_2, or CF_4. Anisotropic etching with removal rates, R, of up to 800 nm/min have been obtained in reactive discharges operated at a pressure of 40 mTorr and a target voltage of -3kV. The physical sputtering rate in pure Ar discharges operated under the same conditions was only 40 nm/min. A combination of in-situ optical emission and absorption spectroscopies have been used to show that in both pure and dilute (up to 90 mole % Ar) halocarbon discharges, physical sputtering of atomic Ga and As is not a primary etching mechanism for GaAs, although ion bombardment does play a critical role in the overall process. Transient glow discharge optical spectroscopy measurements demonstrated that while R increased with increasing Cl/F ratios in the etch gas, the steady state carbon concentration at the GaAs surface also increased indicating that carbon accumulation is not the rate limiting step to etching. Rather, the rate limitation is provided by the desorption kinetics of gallium halides which we believe are ejected primarily (except in pure CCl_4) through ion-assisted processes as the reduced radicals GaF_x and/or $GaCl_x$ (x=1 or 2). We have proposed a phenomenological model to provide a qualitative description of the etching behavior of GaAs in mixed halocarbon/inert gas discharges.

5.3 Laser Stimulated Reactions

In collaboration with the Solid State Physics Division of Eastman Kodak Research Laboratories, epitaxial regrowth of Ge/GaAs heterostructures by scanned laser annealing of amorphous Ge films on GaAs substrates has been studied as a function of laser power and scan rate [5.6]. At least eight regimes representing different film regrowth characteristics were observed. Of these, two were of primary interest. At low powers (between ~ 1.6 and 3.2 W for a beam diameter of ~ 40 μm) and scan rates between 1 and 400 cm/sec, polycrystalline Ge with a (100) preferred orientation was formed by an "explosive" crystallization mechanism. At higher powers, and over a scan rate range of 25 to 400 cm/sec. single crystal metastable $(GaAs)_{1-x}Ge_x$ alloys were obtained by liquid phase regrowth. Typical film resistivities, ρ, were as follows: as-deposited $\rho = 180\Omega$-cm; polycrystalline films, $\rho = 3 \times 10^{-2}$ Ω-cm; single crystal films, $\rho = 9 \times 10^{-4}$ Ω-cm.

5.4 Laser Stimulated Chemical Vapor Deposition*

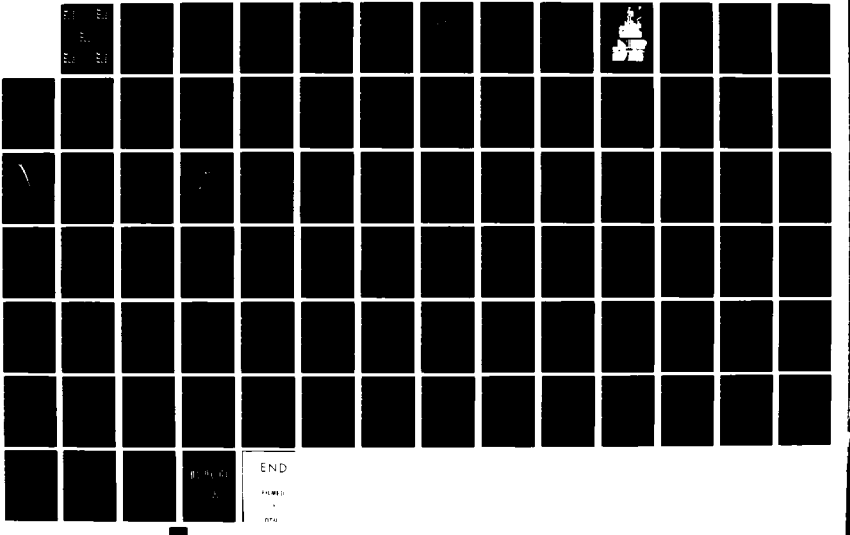
In collaboration with Prof. Eden of the Electrical Engineering Dept. at UIUC, we have grown the first polycrystalline Si and Ge films [5.1] on amorphous SiO_2 substrates (average substrate temperatures $< 120^{\circ}C$) by the photodissociation of SiH_4/N_2 or GeH_4/He mixtures, respectively, using pulsed ArF (193 nm) and KrF (248 nm) excimer lasers. For both Si and Ge, the film growth rate exhibited a strong dependence on laser wavelength and beam intensity I where $1 \lesssim I \lesssim 10$ MW - cm^{-2}. As-deposited films had average grain sizes of up to 0.5 μm and the grains were equiaxed with a random orientation. Ge films grown at slightly elevated temperatures, ~ 300°C, were p-type with a carrier concentration of 2×10^{17} cm^{-3} and a corresponding mobility of 120 cm^2/V-sec. Ge films doped with ~ 10^{20} cm^{-3} Al were obtained by the simultaneous photodissociation of $Al(CH_3)_3$ and GeH_4. Optical absorption and emission experiments are being carried out to investigate photon-molecule gas phase reactions.

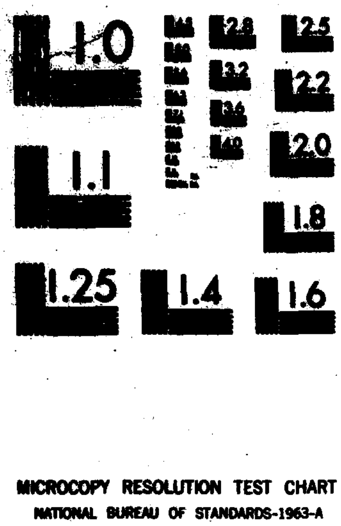
---

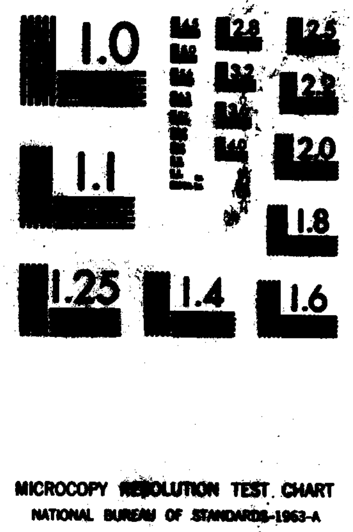
* This work was supported by the Office of Naval Research under contract N00014-81-K-0568.

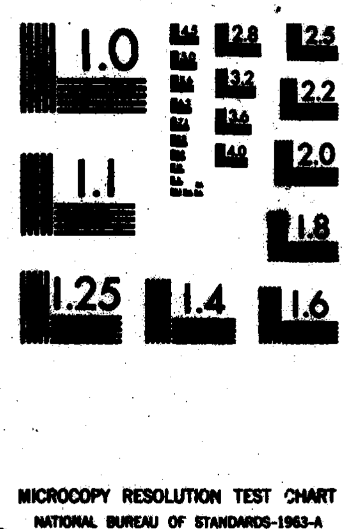
AD-A120 820 ANNUAL PROGRESS REPORT FOR JULY 1 1981 THROUGH JUNE 30 1982(U) ILLINOIS UNIV AT URBANA COORDINATED SCIENCE LAB R T CHIEN ET AL. AUG 82 N00014-79-C-0424 2/2

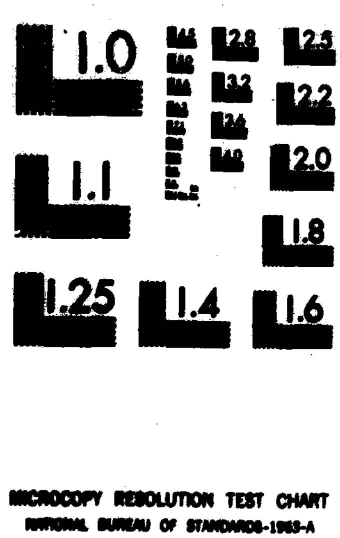
UNCLASSIFIED F/G 5/2 NL

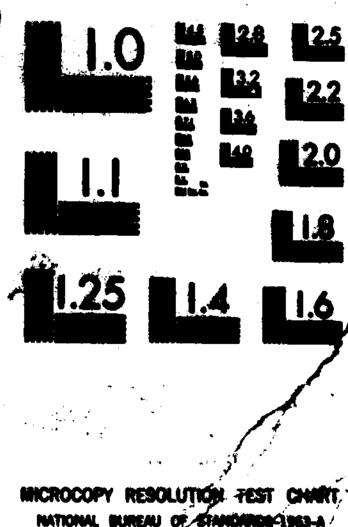



1.0
2.8
2.5
3.2
2.2
3.6
2.0
4.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


1.0
2.8
2.5
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


1.0
2.8
2.5
3.2
2.2
3.6
2.0
4.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


1.0
2.8
2.5
3.2
2.2
3.6
2.0
4.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


1.0
2.8
2.5
3.2
2.2
3.6
2.0
4.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

6. MICROWAVE ACOUSTICS*

Faculty and Senior Staff

B. J. Hunsinger

Graduate Students

E. Bogus	R. Miller	G. Pieters
M. Hoskins	M. Needham	A. Santone

6.1 Objective

GaAs is a unique material in that it has semiconductor properties that make it ideal for high-speed electronic devices, and it has piezoelectric properties that make it usable for acoustic devices. Very powerful monolithic signal processors will be feasible on GaAs because the electronic devices provide the gain and control while the acoustic devices provide the very compact low power fast memory required for signal processing.

When a surface acoustic wave propagates along the metallized surface of a GaAs substrate it produces potential wells buried a few microns or so under the surface that move along with the wave at the velocity of sound. These traveling wave potential wells, associated with the acoustic wave, are used to capture the electrons and transport them in synchronism with the wave. The objective of this research is to investigate electronic transport by the traveling wave potential wells for various configurations of multi-layer GaAs substrates.

6.2 Description and Progress

The principle of electronic transport by surface acoustic waves on GaAs substrates has been demonstrated. The first device demonstrated this characteristic as a delay line which is in many ways similar to a conventional CCD. The charge is injected at one point, propagated along by potential wells, and then collected at a later point. The time during which it remains

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424.

in the substrate represents signal delay. The difference between the acoustic charge transport (ACT) devices and the conventional CCD is that the ACT devices have no gate structures, and the charge is carried strictly by the potential wells of the acoustic wave. The following paragraphs briefly describe the first experiments and the results of those experiments.

A photograph of the device shows the overall layout of the ACT and the physical geometry of the multilayer buried channel structure is described as follows: The layers, grown by molecular beam epitaxy on a [100] cut Cr doped GaAs substrate, consist of a 1.7 μm thick P layer (Na ~ 10^{15} cm^{-3}) and a 4.7 μm N layer (Nd ~ 10^{15} cm^{-3}). The device transfer channel located under the Schottky Barrier region is oriented in the ⟨110⟩ direction, and is delineated by a preferential mesa etch to a depth of 5 μm. Ohmic contacts to the input and output diodes and to the exposed P layer are formed using the liftoff process. After the contacts are alloyed, the Al Schottky barrier, acoustic interdigital transducer, and interconnect pads are formed using standard photolithographic techniques. The interdigital transducer, which has approximately 100 electrode pairs, generates 7.9 μm wavelength SAW over a beam width of 150 wavelengths at a frequency of 367.1 MHz. The transport channel is 1 mm wide and 1.55 mm long corresponding to an acoustic delay between the input and output diodes of 0.5 μs.

The Schottky barrier region is depleted with DC bias and the SAW generated by the transducer propagates from the input diode to the output diode. Charge carriers are injected into the wave by applying a short negative pulse to the input diode. The electrons are bunched and transported along the channel by the potential wells of the SAW. When the wave amplitude is large, the injected electrons are quickly bunched and moved synchronously with the wave, at precisely the sound velocity. Upon reaching the output diode the delayed charge packets are swept out of the wave by the applied reverse bias resulting in a current spike in the output detection circuit.

In the absence of loading and diffusion effects, the minimum traveling wave electric field necessary for the synchronous transport is about 40V/cm. In our experiments the acoustic power is 10 mW resulting in a peak electric field of about 600 V/cm. The fields will be an order of magnitude greater in future experiments. The output diode current obtained when the SAW transducer is driven by a 367 MHz source is found to be a nearly perfect delayed replica

of the input waveform.

There are several fundamental features of the ACT device:

(1) Synchronous electron transport is induced using the SAW as a natural "clock" eliminating the need for transport gates and the multiphase clock drivers.

(2) The interfering "clock" noise is eliminated.

(3) The ACT is expected to be monolithically integratable with high speed electronic components.

(4) High clock frequencies and large time bandwidth products appear to be feasible because the charge transport efficiency is high.

The experimental results show that the ACT has the potential for the implementation of high speed, large time-bandwidth product, large dynamic range, monolithically integrated signal processors.

6.3 Recent Developments in LAW Technology*

6.3.1 Efficient LAW convolvers

Line Acoustic Wave (LAW) convolvers with a measured internal efficiency factor of -40dbm have been demonstrated. At least 10db of the losses are due to bulk wave generation, and resistance in the conductors. If these loss mechanisms are reduced, a -30dbm internal efficiency factor should be possible. This is about two orders of magnitude more efficient than the Surface Acoustic Wave convolvers presently in use.

The dynamic range of LAW devices surprisingly high. Devices implemented with narrow bandwidth IDT transducers placed along the edge have been operated with input power levels in excess of + 27dbm. The LAW convolvers are naturally resistant to second harmonic generation and no saturation affects could be measured at these power levels. However, the wide band LAW IDTs are destroyed while operating at such high powers. The failure mechanisms invariably involve the high electric fields associated with the wideband IDT, and these failures will be reduced with the Multi-Strip Mode

* This work was supported by the U.S. Air Force under contract F19628-81-K-0031.

Converter transducer. (MSMC)

6.3.2 Wideband MSMC LAW Transducers

Broadband MSMC LAW transducers are implemented by generating surface acoustic waves and then converting them to LAWs. The efficiency of the surface acoustic wave to LAW mode conversion process is expected to reach the 1 to 2 db level. It should then be possible to build a MSMC LAW transducer with an insertion loss of about 5db. This will be further reduced by two to three db if unidirectional SAW transducers are used as part of the MSMC. The bandwidth of the MSMC LAW transducer has been increased from 2% last year to the present value of 7% and devices with 20% to 30% bandwidth are presently being processed.

7. SURFACE STUDIES

Faculty and Senior Staff

G. Ehrlich

R. S. Chambers

Graduate Students

S. Abrams
S. G. Brass
B. H. Chin
D. J. Coulman
H.-W. Fink
T. C. Lo
J. L. Vittitow
F. Watanabe
J. D. Wrigley, Jr.

7.1 Diffusion and Reactivity on Metals*

Part of our effort has been concentrated on understanding how polyatomic molecules decompose on a solid; in this work we have been focusing upon the interactions of methane with tungsten surfaces. These interactions are particularly interesting. Decomposition of methane on metals requires a sizeable activation energy and this system therefore affords a good opportunity for exploring the mechanism of such reactions. In the past, our studies have been done on evaporated films; for these we have built up a coherent view of the molecular events on the surface [R1,7.8]. Recent work has stressed the role of surface structure in the decomposition process. For this, new techniques and equipment have been implemented to allow measurements on well-characterized single crystal planes.

In order to follow the interactions of methane, a rather unreactive gas, we have adopted contact potential measurements. These make it possible to establish the surface coverage without perturbing the gas with energetic electrons, high fields, or thermionic sources. The system which has been built for contact potential measurements on single crystal planes is shown schematically in Fig. 7.1. In it a molecular beam of hot gas impinges on a single crystal specimen. Changes in the contact potential arising when the impinging methane decomposes on the surface are measured by a vibrating

* This work was supported by the National Science Foundation under Grants DMR 78-25015 and 82-01884.

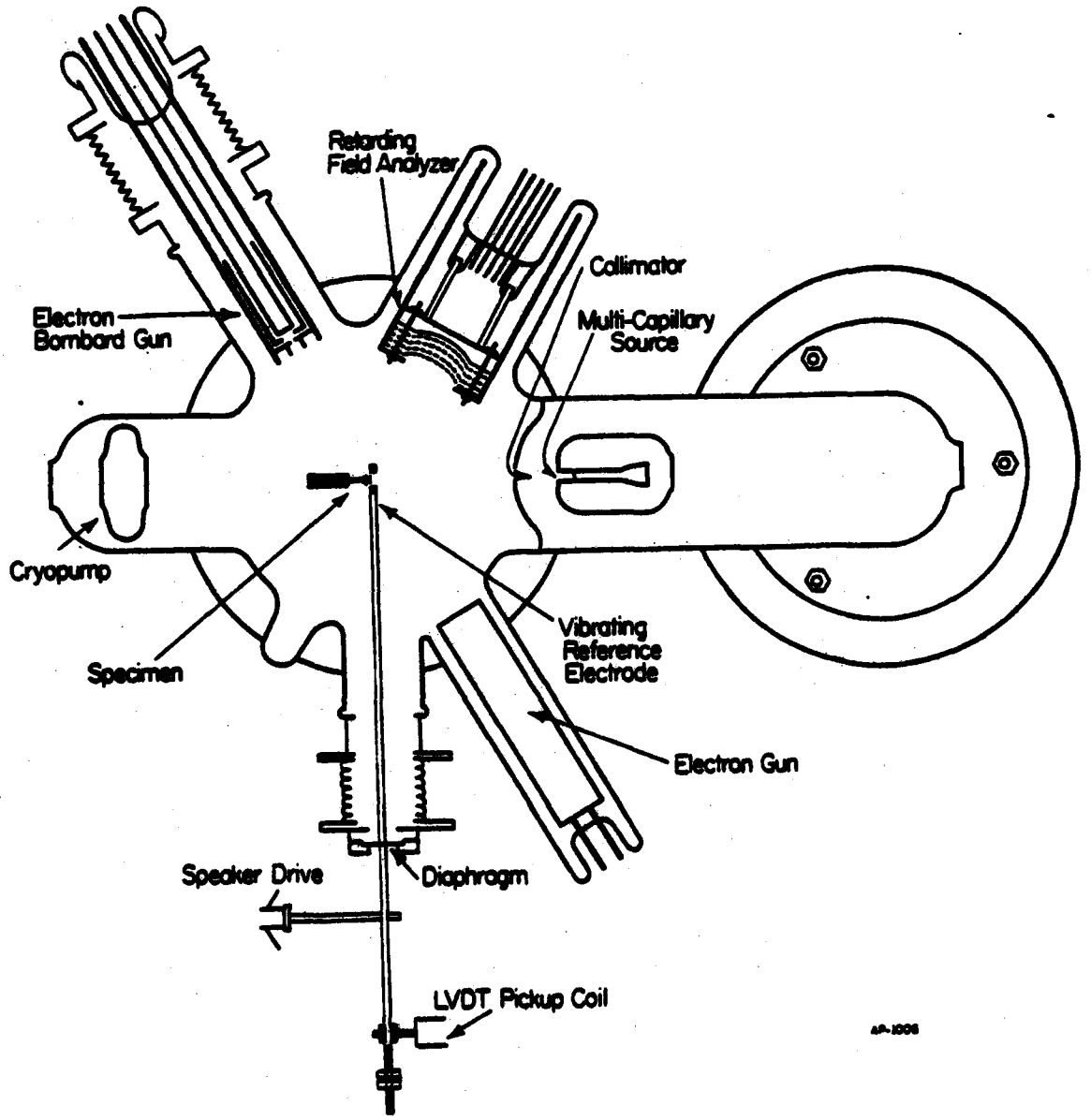


Fig. 7.1 Top view of ultrahigh vacuum system for contact potential measurements of activated chemisorption of methane on single crystal sample.

reference electrode of gold, which is placed in close proximity to the surface before and after gas bombardment. The cleanliness of the sample prior to measurements, as well as the contamination rate in the system, is determined by an Auger system relying on a small retarding analyzer built into the reaction chamber.

The results of studies on the (100) and (211) planes of tungsten are shown in Fig. 7.2. The activation energies differ significantly on the two surfaces, the (100) being more unreactive. There is also a sizeable isotope effect for both, with the barrier for CD_4 exceeding that of CH_4 by more than 20%. In these experiments only the beam temperature is changed; the crystal is maintained at room temperature. These activation energies therefore refer entirely to excitations imparted to incoming gas molecules in order for them to react.

Further experiments, on differently oriented planes of tungsten, are underway in order to more fully expose the relation between surface structure and reactivity toward methane. One thing has definitely been established - the atomic arrangement of the surface plays a very significant role in affecting the activation energy for molecular decomposition.

In a chemical reaction on a solid, the initial act of molecular decomposition is only one of a sequence of steps which finally leads to a new product. At some stage of this reaction molecular fragments must diffuse over the surface to form new chemical combinations. Part of our studies has been aimed at examining how diffusion occurs on macroscopic crystal planes. To carry out these investigations we have built a molecular beam system, illustrated in Fig. 7.3, in which a localized deposit of gas in the form of a line is formed on a single crystal plane. By moving the sample across the fixed electron beam of an Auger spectrometer, the concentration $\underline{c}$ of adsorbed gas can be determined as a function of both time and position. In principle it should therefore be possible to measure the transport over the surface and thus to establish the surface diffusivity.

A start in this effort has been made with preliminary studies of nitrogen on W(100). Measurements on an initial deposit of half a monolayer are shown in Fig. 7.4. In diffusion over the surface we expect a general redistribution of the gas, leading to a broadening of the concentration profile. There is little indication of any such effect in the data. The peak of the

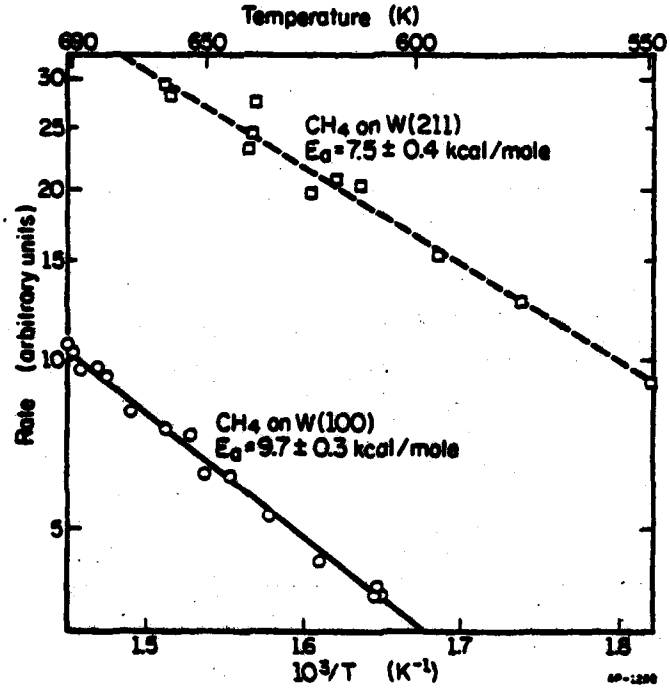


Fig. 7.2 Temperature dependence of methane decomposition on different faces of tungsten. E_a = activation energy for decomposition.

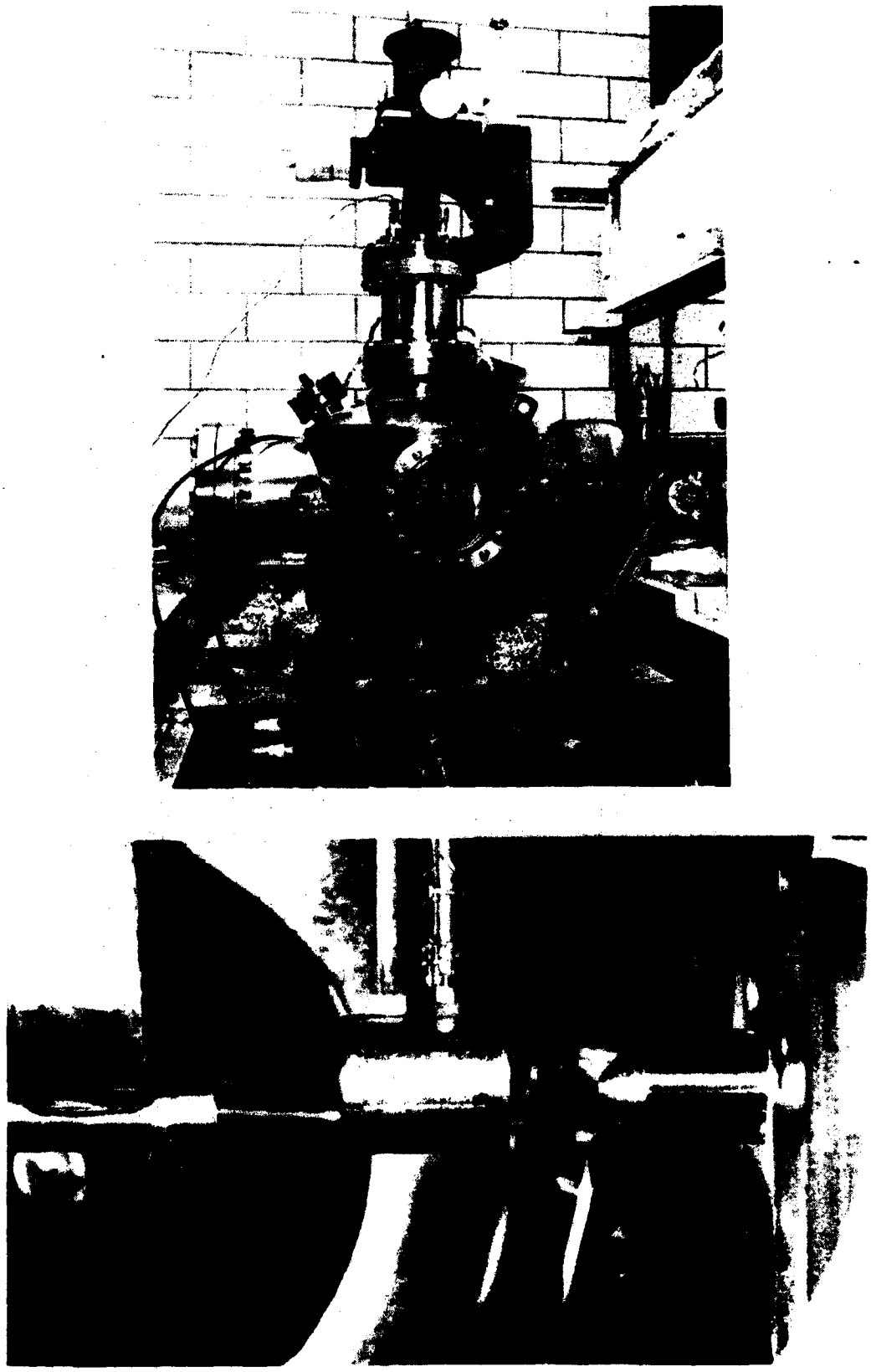


Fig. 7.3. Top: Overview of molecular beam system for surface diffusion studies. Sample manipulator is at top, beam system at right. Bottom: Detail of sample mounting, as seen through bell-jar window. Molecular beam nozzle at right, electron bombardment heater and crystal wafer in center.

concentration profile diminishes significantly with time at 1800°K, but little spreading is discernible. In these measurements, diffusion over the surface is therefore not an important effect. Rather, evaporation appears to dominate. This is quite a surprising result and measurements are in progress to confirm these studies and to define the extent to which this is an intrinsic property of the (100) plane of tungsten.

7.2 Reactions on Silicon*

Work on silicon surfaces has been concentrated upon forming overlayers by electron beam methods, as well as upon studying the spatial stability of the resulting structures [7.9]. As part of this effort we have refined our work on the e-beam formation of silicon nitride. During the past year our studies have shown that the cross-section for dissociation, starting with a monolayer of molecular Nitrogen, is approximately equal to 1×10^{-15} cm^2, rather higher than for gas phase molecules or for nitrogen on metals. A detailed examination of the intensity of the silicon against the nitrogen Auger lines has been made at different stages of electron-beam nitridation, as in Fig. 7.5. This suggests that the first monolayer, a layer of chemisorbed nitrogen, forms by a process of nucleation: after an initial period, in which a number of islands is created, the nitrogen coverage increases through the growth of these islands. The layer so formed then appears to thicken continuously. Silicon nitride structures on the order of 25-30 Å thick have been formed in this way.

Studies on silicon dioxide growth enhanced through electron beam irradiation have also been continued. Measurements on oxidation have been carried out with Si(100) at 25°C as well as at room temperature, keeping other parameters the same. The Auger spectra in Fig. 7.6, obtained after low temperature bombardment, indicate quite clearly that considerably more oxide is formed with the silicon at low temperatures. It is also of interest that in these spectra carbon levels are within the noise limits and do not increase with electron beam irradiation. These measurements suggest that, contrary to some reports, carbon does not act as an important intermediary in e-beam

---

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

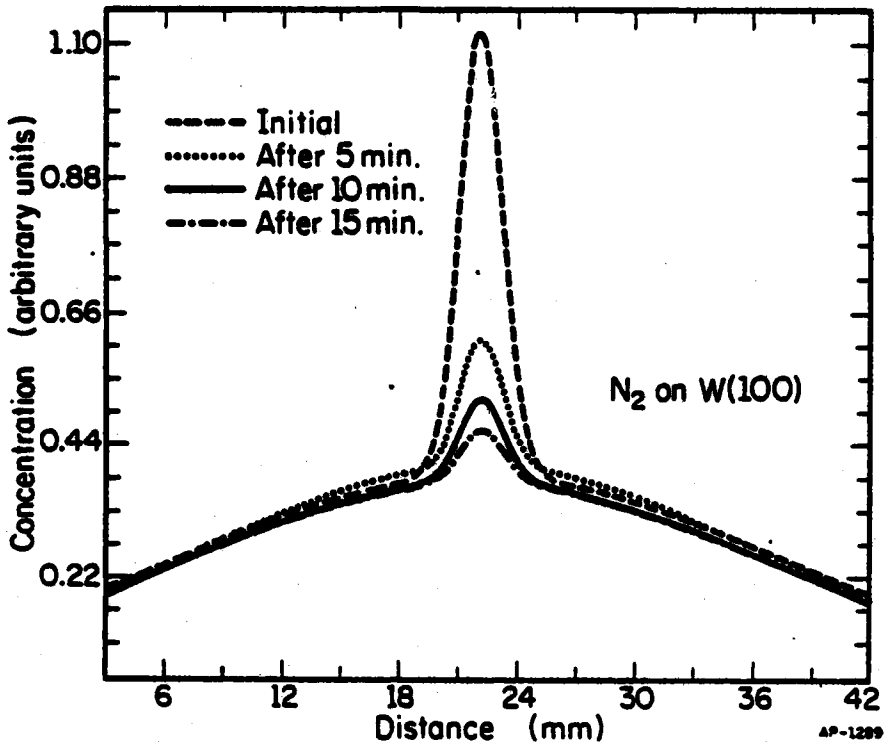


Fig. 7.4 Concentration profiles for nitrogen on W(100) after equilibration at 1300°K.

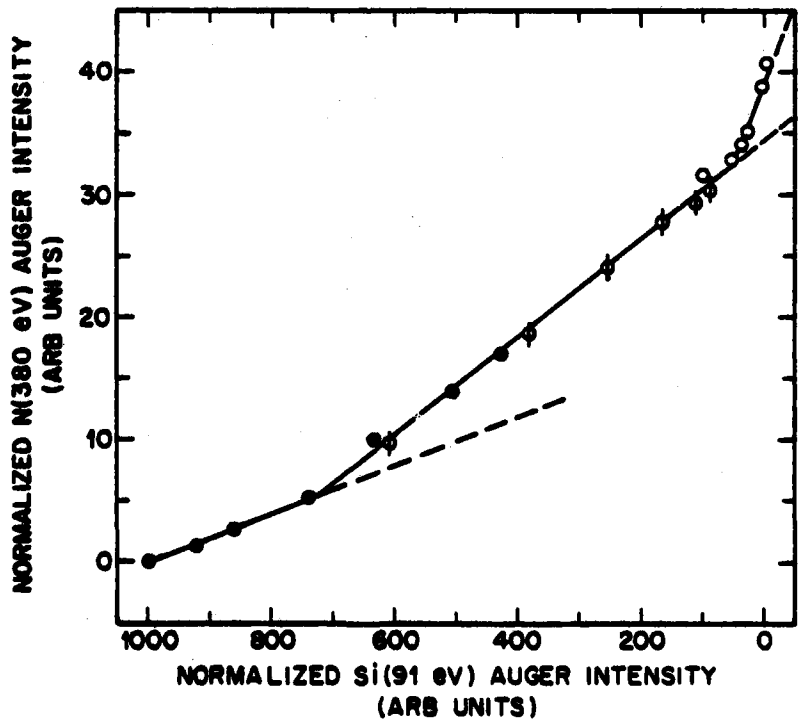


Fig. 7.5 Intensity of nitrogen Auger line versus substrate intensity, for increasing extent of nitridation.

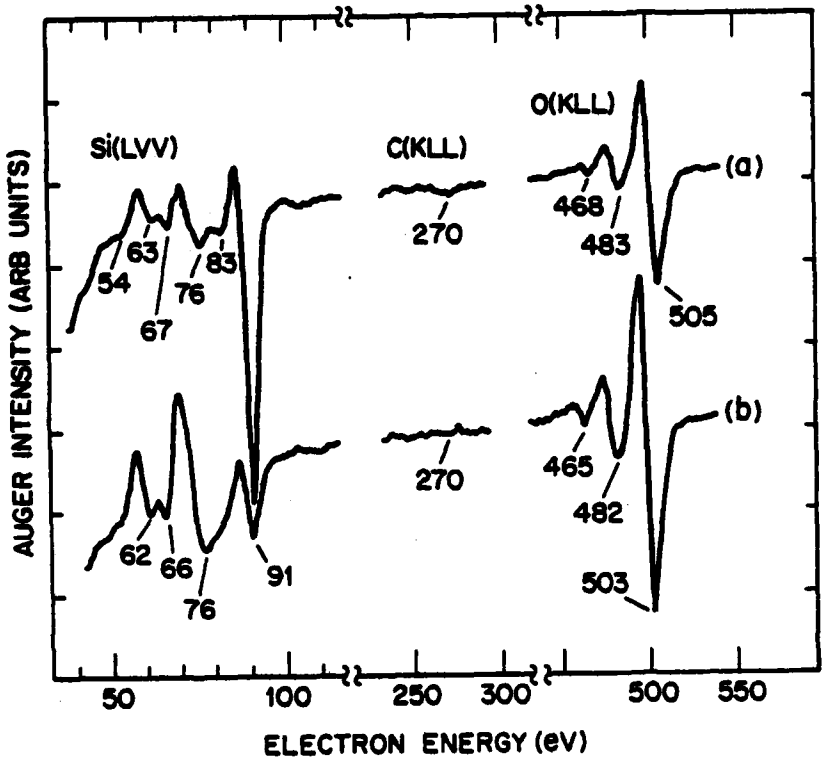


Fig. 7.6 Auger scans for Si(100) at 32 K exposed to 1 x 10^{-5} Torr for 30 min.
(a) No electron bombardment during oxygen exposure
(b) Continuous electron bombardment

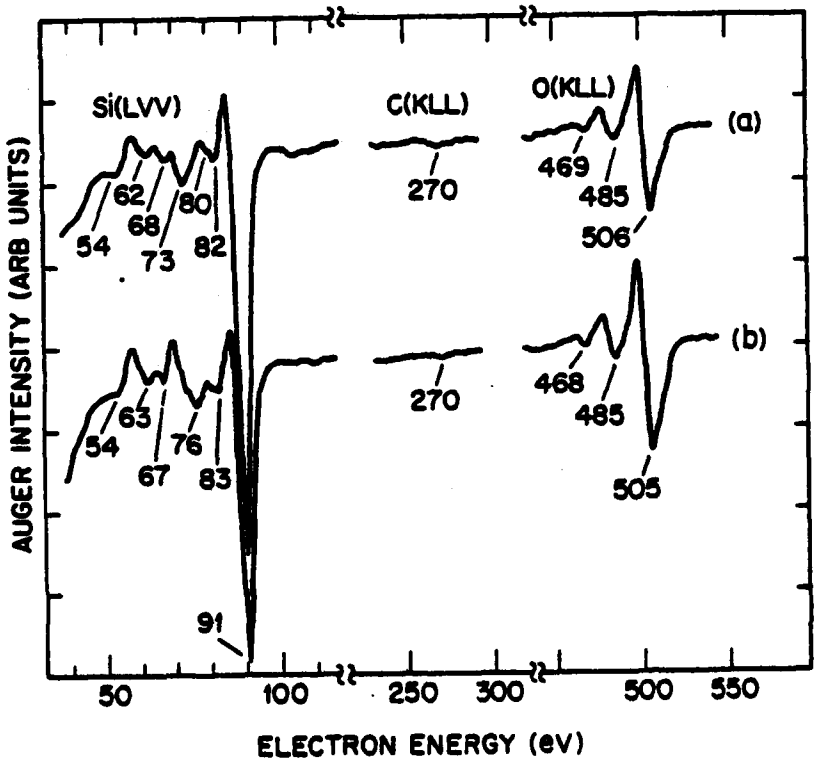


Fig. 7.7 Auger scans for Si(100) at room temperature
(a) No electron bombardment during oxygen exposure
(b) Continuous electron bombardment

oxidation of silicon.

Our work on the spatial stability of these overlayer structures will focus upon surface transport as the important mechanism. Such transport is quantitatively characterized by the diffusivity D in Fick's second law [7.1], which for one-dimensional diffusion appears as

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial c}{\partial x} \qquad (1)$$

One of the problems in surface diffusion is that the diffusivity is generally not a constant at constant temperature, but instead varies with concentration. Under these circumstances Eq. (1) has not been solved in closed form and the question is: How can D be deduced from experiment?

Using the Auger methods described in Section 7.1, the concentration profile, that is the concentration as a function of position, can be obtained for diffusion intervals of different lengths. From one such profile the spatial derivatives can be evaluated; the time derivative at constant concentration should also be available from several such determinations. Using computer modeling we have begun to explore how effective this technique is, and how much data are required for its implementation. In Fig. 7.8 is shown the form of the diffusivity assumed in our trials. This is compared with the values of D derived from measurements of seven concentration profiles. From this preliminary work it appears that our technique has promise. It still remains to explore how significant experimental uncertainties are in affecting the derived diffusivity, and how much data are required for reliable results.

7.3 Atomic Exploration of Crystal Layers*

In an endeavor to better understand the formation of metal overlayers on solids we have been examining the individual atomic steps involved in such processes using the field ion microscope. Diffusion of individual metal atoms is obviously important; we have shown in past studies that atomic diffusion in some systems, at least, may be quite complicated [R2]. On the (110) plane of

* This work was supported by the National Science Foundation under grants DMR 80-24061 and 82-01884.

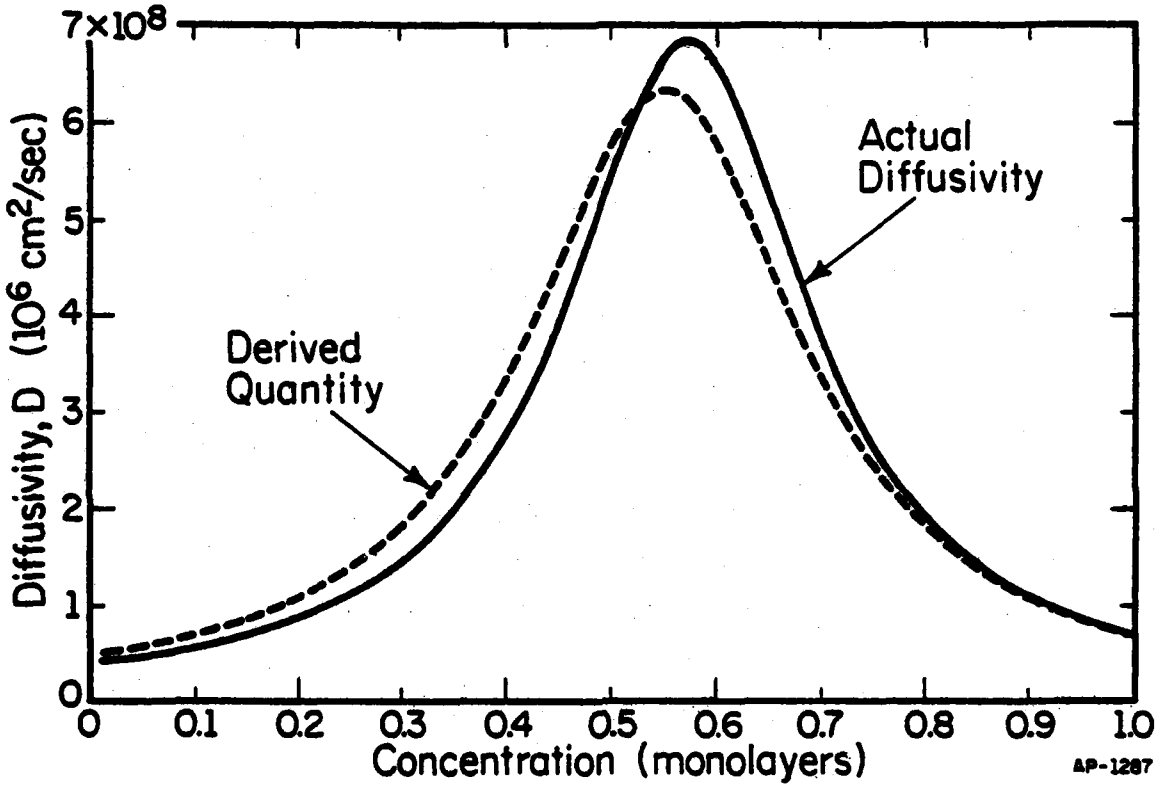


Fig. 7.8 Concentration dependence of diffusivity derived from computer generated concentration profiles, compared with input values.

certain face-centered cubic metals, atomic diffusion occurs by a replacement mechanism in which the adatom displaces the lattice atom, pushing it into an adjacent channel while incorporating itself into the lattice. According to our studies this is how motion takes place on the (110) plane of iridium. Now it is known from work on large scale single crystals that Ir(110) is reconstructed and does not have the atomic arrangement of a (110) plane in the bulk. In contrast, the (110) plane of rhodium is not reconstructed, and on it diffusion is normal. Is there a connection between cross-channel diffusion and surface structure?

Regrettably the atomic arrangement of the planes on which diffusion measurements have been made is not known; we have begun an examination to better define the atomic arrangements. From measurements of the spacing between the [1$\bar{1}$0] rows, we know that Ir(110) produced by low temperature field evaporation has undergone a (2 x 1) reconstruction: the distance between the imaged close-packed rows is twice the normal. This still does not define the positions of the individual atoms at the surface. We have been able to get some idea about this from observations of a sequence of field ion images produced by evaporating one layer of the surface, imaging, evaporating another layer, and then reimaging. The present view of the atomic arrangement of the (110) of iridium, as produced by field evaporation, is shown in Fig. 7.9. The plane is seen to be restructured in a complicated way involving a considerable displacement of many surface- and near-surface atoms. The extent to which other fcc materials undergo similar rearrangements is presently being investigated.

A beginning has also been made at examining the actual formation of an overlayer. In these studies rhenium layers on W(211) have been explored. By using a single rhenium adatom to map out binding sites on the surface it has been possible to establish that rhenium layers are pseudomorphic with the substrate; that is, their structure conforms to that of the W(211) surface. The energetics of rhenium atoms bound to the layer have also been examined. Here most unusual results have been obtained. As indicated in Fig. 7.10, the binding energy of an adatom in a channel adjacent to a large rhenium cluster does not agree even qualitatively with our standard notions. When four sites are available to the adatom, the binding energy at the two center positions is higher than at the ends. That, of course, is as expected. At the center

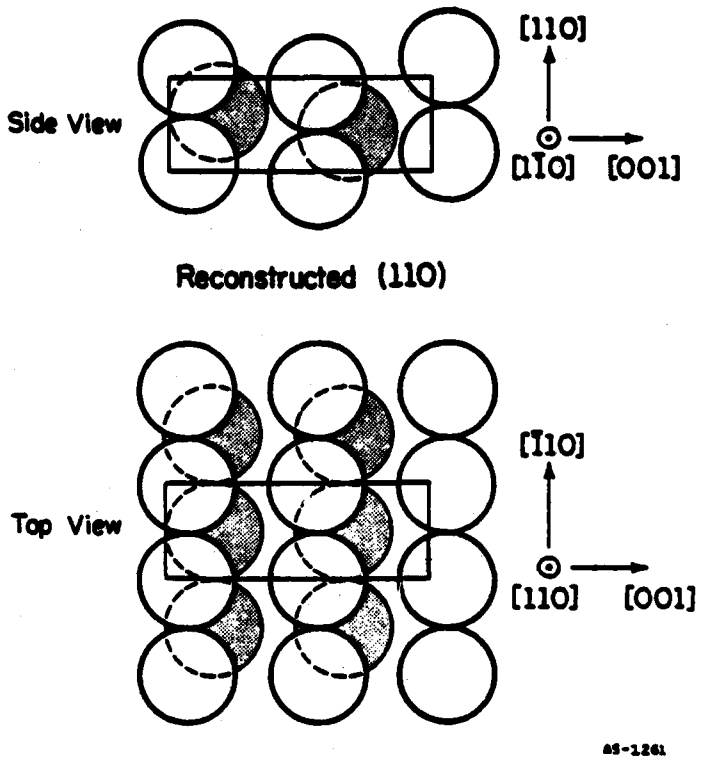


Fig. 7.9 Top- and side-view of reconstructed (110) plane of iridium.

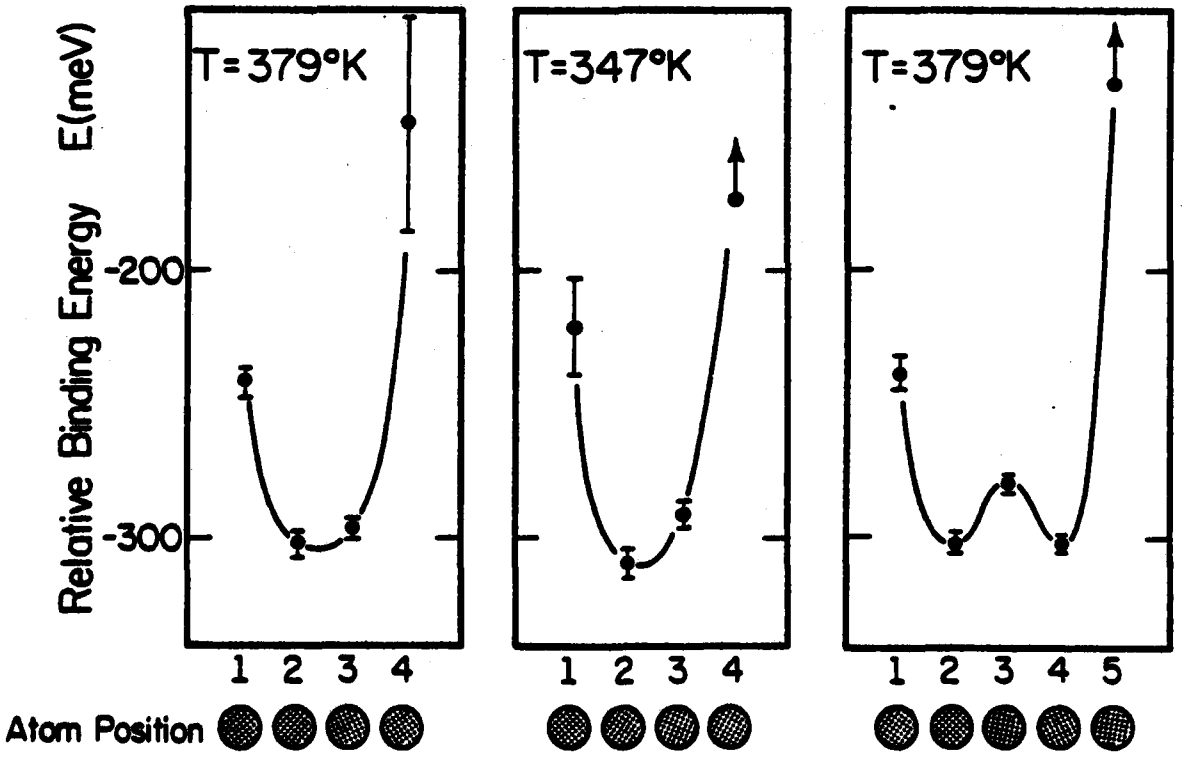


Fig. 7.10 Relative binding energy of rhenium atom at rhenium cluster on W(211).

positions the number of neighbors around the adatom is larger than at the ends; however, when the cluster presents five edge sites, the situation is quite different - the binding of the center site is actually less than at adjacent positions.

If this effect proves general it would have considerable importance for rationalizing the properties of overlayers, and work on atom bindings is therefore continuing.

References

[R1] CSL Annual Report of Progress 1980-1981, 7.1.

[R2] J. D. Wrigley and G. Ehrlich, Physical Review Letters, vol. 44, pp. 661-663, 1980.

8. ELECTROMAGNETIC COMMUNICATION, RADIATION AND SCATTERING

Faculty

Y. Hayashi R. Mittra

Graduate Students

E. Farr S. Ray K. Webb

R. Kastner T. Trinh J. Wilson

8.1 Millimeter-wave Integrated Circuits*

In the past twelve-month period, we have investigated five different aspects of millimeter-wave integrated circuits (MMIC). These are: (i) multimode operation of MMIC with the objective of utilizing the waveguide and components at frequencies that are much higher than that for which the waveguide is originally designed; (ii) theoretical and experimental investigations of fin lines with one or more layers of dielectric and ferrite substrates; (iii) development of new types of planar waveguides for MMIC application; (iv) analytical studies of discontinuities in open waveguides using the newly developed spectral-domain technique; and (v) design of waveguide filters by introducing periodic discontinuities in the planar guide.

Multimoded waveguides are expected to play a very important role in the design of submillimeter-wave systems operating, say, in the 220 GHz window. This frequency range appears to be well-suited for imaging radar application. Since the dimensions of the waveguides and components become extremely small at frequencies above 200 GHz, it is worthwhile to determine whether a waveguide structure designed for the E-Band (80 GHz range) can be utilized in the 220 GHz range. We are currently performing studies on different aspects of this question.

A systematic investigation of this question requires, as a first step,

* This work was supported by Army Research Office Grant DAAG29-82-K-0084 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

the development of an efficient computer program for the determinatiion of the propagation constant, and the computation of the field distribution for the different modes in the guide. Such a program has been developed and tested for the fin-line configuration, which promises to be a good candidate for both the millimeter- and submillimeter-wave ranges. The program is able to accommodate both the isotropic and anisotropic (e.g., ferrite) substrates. Anisotropic substrates are, of course, employed in the design of nonreciprocal components, such as isolators. The theoretical results for the characteristics of the fin line are also being verified experimentally. Plans for testing the multimode waveguides are currently underway. Preliminary results for the propagation measurements look encouraging and a more thorough investigation is currently being planned.

Along with the fin line, we are also investigating other types of shielded, planar waveguide structures which appear to have some unique advantages. One of these is the suspended H-guide shown in Figure 8.1. Its advantages are low metal loss, total shielding and compatibility with other components fabricated by using the suspended H-guide. A theoretical analysis of this guide has been completed and numerical studies are currently being performed. The potential use of the suspended H-guide as a building block for MMIC is also being investigated.

An important theoretical problem arising in the development of MMIC components is the understanding of the behavior of discontinuities in open waveguides and their circuit characterization. Conventional approaches to analyzing closed waveguide discontinuities are not very useful in the investigation of open-region problems, because the open waveguides not only support the usual bound modes, but an infinite, continuous spectrum of unbounded modes. We have been developing a new approach based on the spectral domain technique which appears to be well-suited for geometries which are unbounded in nature. When fully developed, the method is expected to fill an important gap in the array of theoretical or numerical tools available for the analysis of open region discontinuity problems.

Other components which we have studied are filters and periodic and leaky-wave antennas. We have investigated two different kinds of filter designs - array of sandwiched dissimilar dielectric sheets and periodic notch discontinuities in a planar dielectric waveguide. In the recent past, we have

investigated printed metallic strip discontinuities from the point of view of designing leaky-wave antennas. Both theoretical and experimental investigations have been carried out and extensive results have been obtained. Future work will be directed toward designing waveguide filters using periodic strip discontinuities.

8.2 Electromagnetic Scattering and Radar Target Identification*

We have been developing a new spectral domain technique for solving electromagnetic scattering problems involving arbitrary scatterers which may either be dielectric (lossy or lossless) or perfectly conducting. This method has been devised to serve as an alternative to Moment Methods and Asymptotic Techniques for solving EM scattering problems in the intermediate frequency range. The method takes advantage of the simplicity with which the planar source-field relationships are expressed in the spectral domain. The boundary conditions or constitutive relationships, on the other hand, are expressed most simply in the spatial domain. Alternating between the two domains is carried out with the FFT algorithm. A technique that has been applied in the past to planar structures has been generalized to accommodate three-dimensional bodies. This is accomplished by sampling the current distribution on the scatterer over a number of parallel planes, and using the simple spectral-domain interaction relationships between the planes. This new approach is applicable to arbitrarily shaped conducting, dielectric or lossy dielectric scatterers. It has a larger data-handling capacity than that for Moment Methods and is more general than asymptotic techniques. Thus, it provides an efficient, much-needed approach to filling the gap between the low- and high-frequency conventional techniques.

During the past year, additional work has been done on the problem of radar target identification by the method of determining the spatial distribution of scattering centers. It has been found that both specular points and edge diffraction points can be located and categorized by analyzing RCS data with the Prony algorithm. A modified Prony algorithm has been developed to handle the case of split spectrum measurements, i.e., when RCS

* This work was supported by Office of Naval Research Grant N00014-81-K-0245 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

data are gathered in 2 or 3 frequency bands which are not contiguous. We have shown that many of the advantages of wide-band measurements can be obtained by combining data from smaller (and, hence, more practical) subbands.

Progress has been made towards answering the question of whether or not the scattering center description is still valid when corners are rounded or coated with dielectrics. In order to determine this, the forward-scattering problem must first be solved. Computer programs based on the spectral iterative technique, described in the last paragraph, are currently being developed for solving the above-mentioned forward problems.

9. PLASMA PHYSICS*

Faculty and Senior Staff

M. Raether

Graduate Student

S. K. Ault

9.1 Statistical Properties of Plasma Turbulence

The objective of this research is to study the statistical properties of plasma turbulence. The system under investigation is the positive column of a dc-discharge in helium which is unstable with respect to the spontaneous excitation of ion acoustic waves. Electric field fluctuations of the turbulent wave field are picked up by a Langmuir probe and their probability distribution is measured by a fast sampling method. Significant deviations from Gaussian behavior are noticed in the unstable regime. This together with evidence derived from the spectrum points to possible phase and/or amplitude correlations between waves of the kind that is typical for wave-wave coupling. This allows us to draw conclusions as to the nature of the phase and amplitude ensemble of the Fourier components.

---

*This work was supported by the University of Illinois.

10. RAREFIED GAS DYNAMICS AND COMPUTATIONAL GAS DYNAMICS

Faculty and Senior Staff

S. M. Yen

Graduate Students

R. Chamberlain D. R. Hall S. H. Lee

10.1 Rarefied Gas Dynamics

Rarefied gas dynamics deals with non-equilibrium gas flow problems in which microscopic treatment according to kinetic theory is necessary to determine the effect of intermolecular collisions and gas surface interactions on both the microscopic and macroscopic gas flow properties. Such rarefied gas flow problems occur not only in aerodynamics, but also in electronics, aeronomy, environmental fluid dynamics, and other related fields.

The aim of this research program is to develop numerical methods to solve a wide range of problems under conditions far from and near thermal equilibrium. A Monte Carlo method has been developed at the Coordinated Science Laboratory [R1] to solve directly the Boltzmann equation and has been used by the Boltzmann group to solve the Boltzmann equation for several rarefied gas flow problems under a wide range of nonequilibrium and boundary conditions [R2-R7]. The solutions we have obtained yielded detailed microscopic and macroscopic non-equilibrium properties, most of which have never been treated and studied before. We have also studied numerical solutions of other kinetic equations and other numerical methods to solve rarefied gas flow problems, including the direct simulation technique.

Nonlinear evaporation-condensation problems are encountered in such diversified areas as upper atmosphere meteorology, the cooling of nuclear reactors, design of space experiments, petrochemical engineering, vacuum technology, and the interaction of high power laser radiation with metal surfaces. The treatment of these problems requires first the consideration of vapor kinetics problems characterized by the nonequilibrium vapor motion in a

Knudsen layer at the interphase boundary. Under a joint research effort, we have successfully solved the evaporation problem [R8]. Our Boltzmann solutions establish the validity of the Krook solution and Ytrehus' kinetic theory approach [R9]. Ytrehus' approach can be used to calculate the jump conditions across the Knudsen layer and the net mass, momentum and heat fluxes [10.3] and, together with the conventional continuum method, to calculate the flow parameters at the outer edge of the Knudsen layer for problems in which evaporation occurs at the interphase boundary.

Studies have also been made for the condensation problem [10.2]. The non-equilibrium vapor near a condensing surface differs from that near an evaporating surface and its behavior is more complex. Our Boltzmann solutions yield distinct non-equilibrium behavior in the Knudsen layer of condensing vapor. The condensation rate as a function of pressure ratio was found to depend strongly on the substance parameter β which is proportional to the ratio of the latent heat and its liquid surface temperature. Some of our results were found to be in agreement with those obtained by using the simple approaches of Oguchi [R10] and Ytrehus [R11].

We plan to study further the evaporation and the condensation problems by considering more complex flow and boundary conditions.

10.2 Naval Hydrodynamics*

Free surface wave problems encountered in naval hydrodynamics are characterized by complexities in flow geometry, flow features and boundary conditions. The flow has an unknown free surface and it is propagative and transient. The boundary condition at the free surface is of a mixed, parabolic type and it contains highly nonlinear terms. In the steady state, there also exists a radiation boundary condition, since the waves, once generated, propagate downstream. These complexities have led to several computational difficulties: accurately accommodating the free surface geometry, satisfying the boundary condition uniformly over the free surface, creating the radiation boundary condition and implementing the boundary condition at the contact line of the free surface with the solid surface of a

* This work was supported by the Office of Naval Research under Contract N00014-80-C-0740.

partially submerged body.

In the initial phase of our study, we have developed two time-dependent numerical schemes with Eulerian grid systems for solving steady and unsteady potential flows for nonlinear free surface problems. In one method [R12,R13,R15], we use the finite element method to deal with the geometrical complexity and the free surface boundary condition of the nonlinear free surface problems. In this scheme, the finite element method is used to make the field calculation and the finite difference method is used for the time evolution. We have used this method to solve two problems: a pressure distribution moving with a constant speed and a moving submerged elliptical cylinder or a symmetrical hydrofoil.

We have also developed an explicitly time-dependent finite difference scheme [R14,R16]. We have used this method to solve two problems: a pressure distribution moving with a constant speed and an elliptic cylindrical, surface-piercing strut accelerating from rest. Our solutions serve to demonstrate the feasibility of using the method to solve two-dimensional as well as three-dimensional problems.

The results of the initial phase of our study were presented at the Second International Conference on Numerical Ship Hydrodynamics [R16].

In both numerical schemes mentioned above, the computational domain is expanded downstream periodically during the computation as the disturbance on the free surface is propagated close to the downstream boundary. Therefore, the undisturbed condition is applied on the cut-off downstream boundary.

In order to obtain the longer time and steady state solutions, we use a fixed downstream boundary set close to the disturbance so that we can increase the computation efficiency by dealing with a small computational domain. The second phase of our study has been focused on the application of our numerical schemes to the nonlinear free surface problems with a fixed, small computational domain. We have studied two approaches. In each approach, we have used Orlanski's method [R17,R18] to implement the open boundary condition at the outflow boundary. The two approaches differ in the treatment of high frequency errors that appear in the solution and that inhibit accurate treatment of the open boundary condition. In the first approach, we used filtering to minimize high frequency errors. However, this was found to be effective only at an early time; therefore, it is suitable only for obtaining

transient solutions. In the second approach, we used damping in our time marching schemes. Damping was found to be more effective in controlling high frequency errors. Transient and steady state solutions have been obtained for the pressure distribution and the accelerating strut problems.

The results of the second phase of our work were presented at the Third International Conference on Numerical Ship Hydrodynamics [R19].

We are now in the third phase of our research. The objective of the study in this phase is to apply our method to the ship wave problem. We have chosen the ship of Wigley shape as our first problem. The hull shape of this ship is shown in Fig. 10.1. The numerical method we use has the following features:

(1) the mesh system accommodates both the free surface and the hull surface,

(2) the nonlinear free surface condition is satisfied accurately, and

(3) the computation efficiency for the field calculation is increased by using the successive line over-relaxation method.

The computer program to implement our method for the Wigley ship has been written and preliminary calculations for the early times have been made.

10.3 Aerodynamics

The objective of one of our studies for aerodynamic problems is to solve directly the Euler equation in the entire compressible flow regime: subsonic, transonic and supersonic. There are several reasons we wish to do so. One is to consider the rotationality in the flow. The other is to facilitate error study of the calculation since the same basic equation and the same numerical method are used in the entire flow regime. Our initial effort is to study the numerical solution of compressible flow over an axi-symmetric triconic body. We selected the implicit factored scheme which was developed by Warming and Beam [R20] to solve the Navier-Stokes equation. We used the AIR3D Navier-Stokes computer program developed at NASA/AMES and adapted by Nietubicz [R21] for axi-symmetric flows. We developed and used a mesh generation system designed for the triconic body. In addition, we revised the implementation of several boundary conditions.

We have obtained the Euler solution for $M_\infty = 0.5$ to 2.75. In order to speed up the convergence, we use the solution for a lower Mach number to

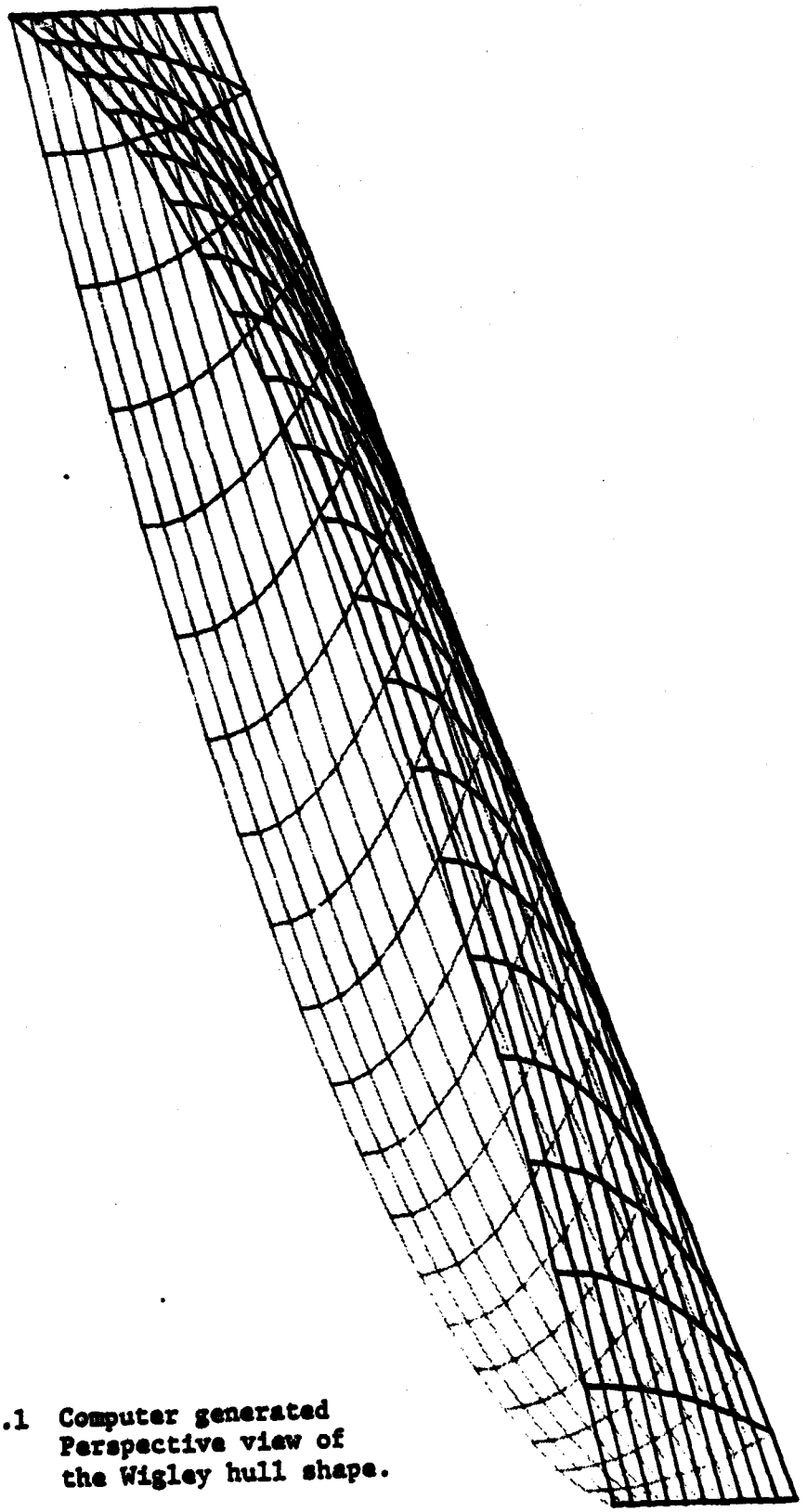


Fig. 10.1 Computer generated Perspective view of the Wigley hull shape.

initialize the solution of a higher Mach number. The mesh system had to be refined whenever necessary for the calculation of flow for a given Mach number.

Fig. 10.2 shows the surface pressure distribution, C_p vs x for M_∞ = 0.5, 0.95, 1.2 and 2.75. These results are compared with calculations by Gustafson [R22], who used a panel method for potential flow for M_∞ = 0.5, relaxation method for transonic flows for M_∞ = 0.95 and 1.2 and a finite difference method to solve the Euler equation for the shock layer for M_∞ = 2.75. The local Mach number contour lines in the physical domain for M_∞ = 0.95, 1.2 and 2.75 are shown in Fig. 10.3.

References

[R1] A. Nordsieck and B. L. Hick, "Monte Carlo evaluation of the Boltzmann collision integral," Rarefied Gas Dynamics, Academic Press, p. 675, 1967.

[R2] B. L. Hicks, S. M. Yen and B. J. Reilly, "The internal structure of shock waves," J. Fluid Mechanics, vol. 53, Part I, p. 85, 1972.

[R3] S. M. Yen, "Monte Carlo solutions of the nonlinear Boltzmann equation for problems of Heat transfer in rarefied gases," International J. of Heat Mass Transfer, vol. 14, p. 1865, 1971.

[R4] S. M. Yen, "Numerical solutions of non-linear kinetic equations for a one-dimensional evaporation-condensation problem," International J. of Computers and Fluids, vol. 1, p. 367, 1973.

[R5] S. M. Yen and W. Ng, "Shock wave structure and intermolecular collision laws," J. of Fluid Mechanics, vol. 65, Part I, p. 127, 1974.

[R6] S. M. Yen, "Solutions of kinetic equations for the nonequilibrium gas flow between emitting and absorbing surfaces," Rarefied Gas Dynamics, DFVLR-Press, vol. 1, p. A.15-1, 1974.

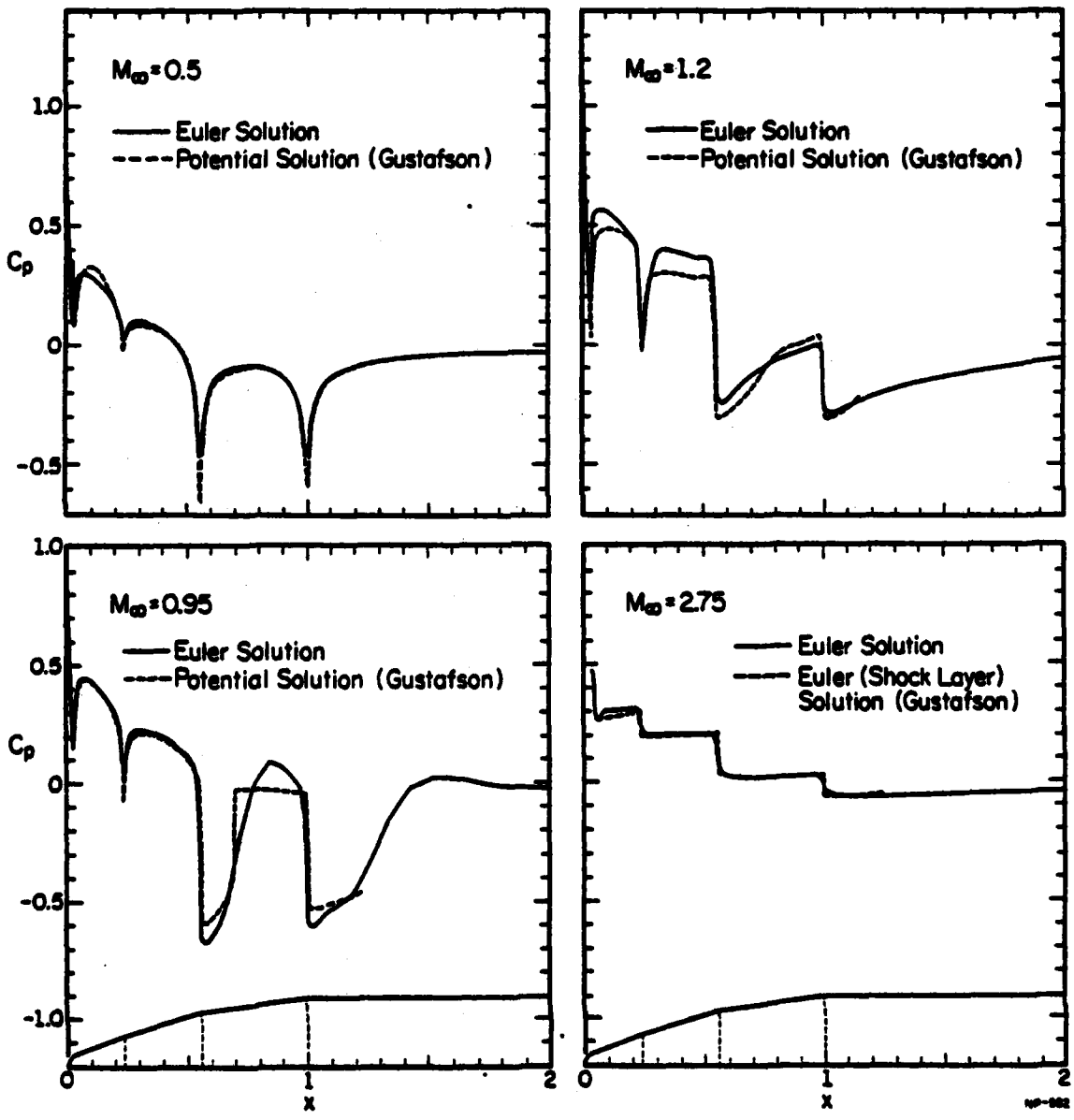

M_∞=0.5
Euler Solution
Potential Solution (Gustafson)
M_∞=1.2
Euler Solution
Potential Solution (Gustafson)
M_∞=0.95
Euler Solution
Potential Solution (Gustafson)
M_∞=2.75
Euler Solution
Euler (Shock Layer) Solution (Gustafson)
C_p
X
1.0
0.5
0
-0.5
-1.0
0
1
2

Fig. 10.2

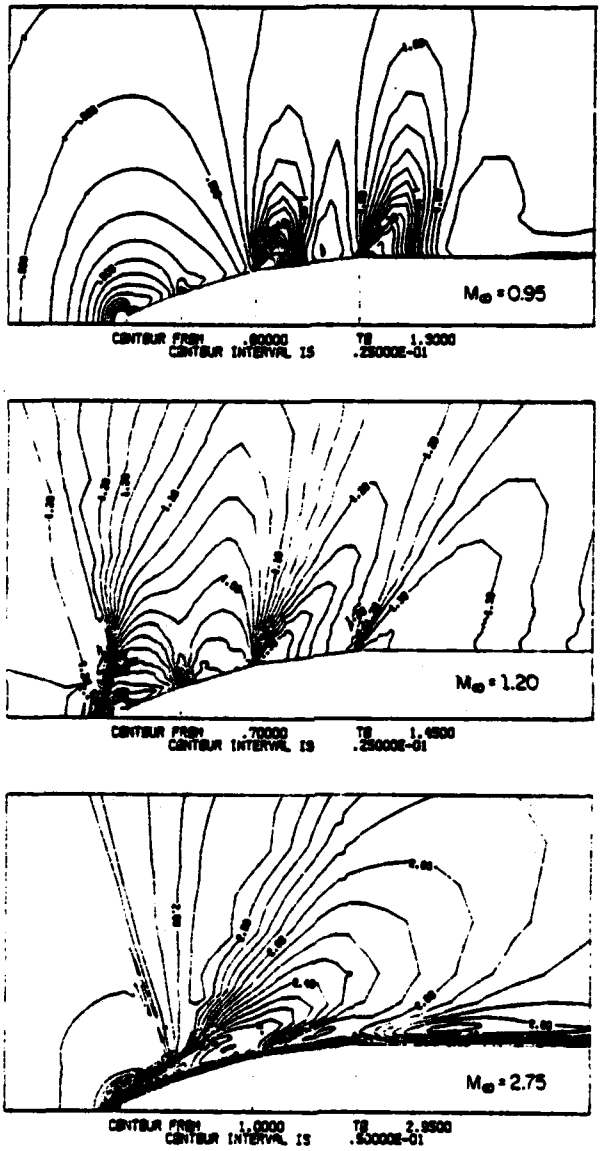

M∞ = 0.95
CONTOUR FROM .80000 TO 1.3000
CONTOUR INTERVAL IS .25000E-01
M∞ = 1.20
CONTOUR FROM .70000 TO 1.4500
CONTOUR INTERVAL IS .25000E-01
M∞ = 2.75
CONTOUR FROM 1.0000 TO 2.9500
CONTOUR INTERVAL IS .50000E-01

Fig. 10.3

[R7] S. M. Yen, "Solution of Boltzmann and Krook equations for heat transfer problems with Maxwell and evaporative boundary conditions," Proc. 7th International Symposium on Rarefied Gas Dynamics, vol. II, p. 53.

[R8] S. M. Yen and T. J. Akai, "Numerical solutions of the Boltzmann and Krook equations for a one-dimensional Effusion-Evaporation Problem," Rarefied Gas Dynamics, Progress in Astronautics and Aeronautics, vol. 51, p. 1175, 1977.

[R9] T. Ytrehus, "Theory and experiments on gas kinetics in evaporation," Rarefied Gas Dynamics, Progress in Astronautics and Aeronautics, vol. 51, p. 1195, 1977.

[R10] M. Hatekeyama and H. Oguchi, "Kinetic theory approach to nonlinear condensation of flowing vapor," Proc. 11th International Symposium on Rarefied Gas Dynamics, vol. 2, p. 1293, 1979.

[R11] T. Ytrehus and J. Alvestad, "A Mott-Smith solution for nonlinear condensation," AIAA Progress in Aeronautics and Astronautics (to appear).

[R12] S. M. Yen and K. D. Lee, "Application of finite element method to potential flow problems," Proc. Second International Symposium of Finite Element Methods in Flow Problems, p. 539, 1976.

[R13] S. M. Yen and K. D. Lee, "Design criteria and generation of optimum finite element meshes," Sixth International Conf. on Numerical Methods in Fluid Dynamics, Tbilisi, USSR, June 1978.

[R14] S. M. Yen, K. D. Lee and T. J. Akai, "Finite element and finite difference solutions of nonlinear free surface wave problems," Proc. Second International Conf. on Numerical Ship Hydrodynamics, p. 305, 1978.

[R15] K. D. Lee, "Application of the finite element method to potential flow problems," Report T-32, Coordinated Science Laboratory, 1976.

[R16] T. J. Akai, "Numerical solutions of nonlinear potential flows with free surfaces," Report T-30, Coordinated Science Laboratory, 1976.

[R17] Robert K. C. Chan, "Finite difference simulation of the planar motors of a ship," Proc. Second International Conf. on Numerical Ship Hydrodynamics, p. 39, 1978.

[R18] L. Orlanski, "A simple boundary condition for unbounded hyperbolic flows," J. of Computational Physics, vol. 21, p. 251, 1976.

[R19] S. M. Yen and D. R. Hall, "Implementation of open boundary conditions for nonlinear free surface wave problems," Proc. of the Third International Conf. on Numerical Ship Hydrodynamics, p. III-2-1, 1981.

[R20] R. Beam and R. F. Warming, "An implicit factored scheme for the compressible Navier-Stokes equations," AIAA Paper 77-645, June 1977.

[R21] C. J. Nietubicz, T. H. Pulliam, and J. L. Steger, "Numerical solution of the azimuthal-invariant thin-layer Navier-Stokes Equations," AIAA Paper 79-0010, Jan. 1979.

[R22] T. Gustafson, Private communications.

11. COMPUTER SYSTEMS

Faculty and Senior Staff

J. A. Abraham E. S. Davidson J. H. Patel

Graduate Students

S. Abrams	L. Hanes	R. Norton
D. Archer	P. Hsu	D. Paul
P. Banerjee	K. Huang	L. Pedersen
P. Bose	N. Jha	A. Pleszkun
D. Brahme	J. Jou	H. Pollard
R. Chillarege	B. Kahhaleh	J. Rahmeh
B. Chin	M. Kaplan	W. Rogers
J. DeGroat	J. Kinsel	A. Saleh
P. Emma	G. Koob	G. Sohi
K. Fuchs	S. Laha	J. Theodosiou
L. Fung	D. Lilja	C. Trempel
J. Gordon	G.-P. Mak	C. Ufferheide
M. Graf	F. Massa	C. Wong
D. Halperin	G. McNiven	A. Yu

11.1 Functional Fault Models from Physical Failures*

Typical physical failures observed in the field were simulated at the circuit level on basic nMOS and CMOS cells to study their effect at the logic level. We have found that many physical failures could not be modeled by existing fault models such as the stuck-at models. The results of these detailed studies were used to develop a multi-valued algebra which could be used to predict MOS circuit behavior under physical failures for large modules. Using the rules of the algebra, a simulator has been implemented in

* This work was supported by VHSIC (U.S. Naval Electronics System Command) under contract number N00039-80-C-0556.

PASCAL under VAX/UNIX; this is about two orders of magnitude faster than circuit simulation. These studies have also been used to derive functional level fault models for modules such as Programmable Logic Arrays and Decoders which have some structural regularity.

From the circuit simulation study, we have also derived approximate formulas for estimating the changes in the inversion voltage and gate delay due to a shift in the threshold voltage. Once the behavior of a fault-free circuit is determined by circuit simulation, the formulas can be used to estimate the changes in the circuit behavior due to a threshold fault.

11.2 Test Generation for Complex Digital Systems*

As integrated circuits increase in complexity, the problem of testing them is becoming more and more difficult. We have found that our approach of describing physical failures at the functional level and deriving tests at this level is an excellent solution to this problem. This technique has been successfully applied to deriving tests for memories, programmable logic arrays, and regular logic structures. A new and efficient memory test algorithm which will detect interactions between multiple cells in a memory has been derived; previous work had restricted the number of interacting cells to two or three. We have also found a method to design easily testable logic structures directly from a high-level language description of the desired function. The inherent structure is a tree which provides a high-speed realization of the function. An efficient algorithm for testing general tree structures has also been found.

The current trend in designing complex systems is toward the use of structured techniques, and this has motivated the design of a fault simulation technique which takes advantage of structured design in order to reduce the complexity of simulation. A concurrent fault simulator which hierarchically evaluates the input design has been designed and is being coded to evaluate the performance.

---

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424.

11.3 Concurrent Error Detection Techniques*

A functional error model has been formulated for information transfer and storage in a microprogrammable control unit, and coding and addressing techniques have been developed for detecting these errors concurrently with normal operation. These techniques are also applicable to detecting addressing failures in memory systems.

We have developed an error-detection scheme based on time redundancy; this scheme, called Recomputing with Shifted Operands (RESO), is applicable to both arithmetic and logic operations. It has been extended to include multiply and divide arrays. This scheme has also been extended to correct all functional errors in a typical adder using time redundancy when the errors are confined to a small area of the chip.

A study of programmable logic arrays (PLAs) has found that physical failures will result in unidirectional errors at the outputs. Design procedures have been found to design PLAs with concurrent error detection using unidirectional error-detecting codes such as Berger codes or m-out-of-n codes.

11.4 Design of Modules with Concurrent Error Detection*

We have designed a parallel-pipelined module which performs the butterfly operation, the control, and the data storage of the Fast Fourier Transform. Eight butterflies are performed on one eight-bit slice chip. Concurrent error detection was achieved by RESO for the ALU, parity for the memory and data paths, and by duplicating the control. The chip has been laid out in nMOS technology.

A residue number-encoded digital filter architecture has been designed and is being laid out for nMOS fabrication. It is organized as a multiple stream, pipelined structure allowing high device utilization and modularity. The residue system allows fault tolerance and graceful degradation.

An architecture and an organization have been defined for a useful multiple instruction stream shared pipeline processor implementable on a single chip.

---

* This work was supported by VHSIC (U.S. Naval Electronics System Command) under contract N00039-80-C-0556.

A cell for a systolic array processor has been designed and is being laid out using a CMOS process in cooperation with ESL, Inc. It incorporates a two-stage pipeline and uses RESO and parity for concurrent error detection. Its primary application is for Finite Impulse Response filtering.

An address generator chip, which will rapidly generate memory addresses for array elements in loops under control of a host processor, is being designed and laid out using CMOS rules in cooperation with ESL, Inc. It allows up to eight indices in the array. The appropriate stride constants are stored in the chip prior to entering a loop.

The design and nMOS implementation of a microprogram control unit with control capability similar to the AMD 2910 microprogram sequencer have been undertaken. The concurrent error detection techniques developed in the group for microprogram control units are being implemented in this design.

A design in nMOS technology of a crossbar switch which could be potentially used in a multistage network of the delta type has been completed. Two types of chips, a control chip and a data chip, have been laid out for this purpose. We are now working on incorporating concurrent error detection in the module.

A complex multiply-accumulate chip with concurrent error detection has been laid out in nMOS technology. This chip uses RESO for concurrent error detection.

11.5 Fault-Tolerant Matrix Algorithms for Processor Arrays*

Classical techniques for fault tolerance are based on replications of modules, with the errors from a failed module being masked by the correct outputs from the good modules. We have found very efficient techniques for fault tolerance in matrix operations where the inherent redundancy in the algorithms executing on array processors is used to detect and correct errors from a failed processor. The techniques use the idea of checksums in a novel fashion, and the redundancy required is only of the order of (1/n), where n is the size of the array. The method can be used either with mesh-connected or systolic arrays. By tailoring the fault-tolerance technique to the algorithms

* This work was supported by VHSIC (U.S. Naval Electronics System Command) under contract N00039-80-C-0556.

used and to the structure of the array processor system, we are able to achieve error detection and correction at a cost far less than that of using a general replication technique.

11.6 A Sparse Matrix Processor*

The efficiency of sparse matrix computations can be dramatically improved by using matrix sparsity patterns to eliminate conditional branches and array index calculations. We have extended this technique for highly concurrent parallel processors. Static scheduling of sparse matrix computations at compilation time results in lower overhead and higher resource utilization. Generating addresses and other control information at the site where it is used reduces the amount of interchip communication during execution. A compiler-architecture system using this approach has been proposed and evaluated for its performance on sparse LU decomposition and sparse matrix multiplication. High resource utilization (over 80%) was observed for hardware configurations with up to 128 processors when large matrices (400x400, 5 elements per row) were used.

11.7 Pipelined Architectures**

We have been able to construct mathematical models of instruction-unit pipelines with probabilistic flow-perturbing exception conditions. These models are valid over wide ranges of system parameters. A trace-processing algorithm which yields exact performance measurements of programs which are subject to data and control-flow dependencies in pipelines has been developed, and an exact residual-time model has been derived for hardware dependencies in pipelines. These are the first known models for instruction pipelines which can effectively evaluate performance under effects such as cache miss, resource conflict, error retry, branch and data dependency, and function-dependent segment time variation.

A study of the recovery of pipelined systems from transient faults has

---

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

** This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424 and by VSHIC (U.S. Naval Electronics System Command) under contract N00039-80-C-0556.

produced an approximation for the distribution of faulty periods which compares very favorably with simulation.

11.8 Structured Memory Access Architecture*

Our Structured Memory Access (SMA) architecture represents a significant breakthrough of the "von Neumann performance bottleneck" by reducing memory wait time and by eliminating a majority of the memory references required to execute a program. This breakthrough is achieved by decoupling the address generation process from the data computation process. A simulation, running a Gaussian elimination program, showed the performance to be a linear function of the pipeline lengths of the Memory Access Processor, the memory, and the Computation Processor. The SMA achieves about a 50% reduction in memory references over conventional machines running optimized code.

11.9 Multiuser Multiprocessors with Private Cache Memories**

In the context of a multiuser multiprocessor system with private cache, we have considered the write-through versus the write-back policy of main memory update. The advantage of the write-back policy is that the bus traffic is reduced in comparison to the write-through policy. It is usually assumed that the coherence problems of write-back require hardware such as global directories to detect potential coherence problems. For this reason, a write-through cache is usually used which provides coherence for all transactions. We have, however, suggested ways to avoid these coherence problems in user code and have examined the potential savings, in terms of bus traffic, by using a write-back rather than a write-through cache. Using a detailed instruction level simulation, we found that in the typical case the write-back policy, compared to write-through, will allow more than twice the number of processors on the bus at a given traffic level.

---

* This work was supported by VSHIC (U.S. Naval Electronics System Command) under contract N00039-80-C-0556.

** This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424 and by VSHIC (U.S. Naval Electronics System Command) under contract N00039-80-C-0556.

11.10 Design Verification Techniques*

A top-down hierarchical design automation facility is being developed which includes design verification capability. A graphics input package has been interfaced to the Livermore SCALD II package, and a mechanism for including functional descriptions of modules has been developed for verification. An automated reasoning program developed by Argonne National Laboratory is being used to determine equivalence between the functional description of a module and the structure-driven combination of the functional descriptions of its submodules.

* This work was supported by VSHIC (U.S. Naval Electronics System Command) under contract N00039-80-C-0556.

12. APPLIED COMPUTATION THEORY*

Faculty and Senior Staff

D. J. Brown | M. C. Loui | F. P. Preparata
X. Jin | D. E. Muller | S. Swamy

Graduate Students

G. F. Bilardi | T. Bolognesi | M. Pracchi

12.1 Introduction

Current technology requires the development of efficient computational techniques and the analysis of the capabilities of various models of computation. We are concerned with the resources - such as time, equipment, memory, interconnection - that are used or needed in the algorithmic solution of given problems. This dynamic discipline, concrete computational complexity, is important for both hardware and software applications, and it also contributes to our basic understanding of computing. It is only natural that the great technological innovations represented by Very-Large-Scale-Integrated (VLSI) Circuitry have had a substantial impact on this field, opening new horizons and posing challenging problems. Much of our current research (organized below in five subsections) has been motivated by this revolution.

12.2 Parallel Computation in VLSI

Parallel computation provides a fundamental answer to the need to increase computer processing power, and VLSI is the natural habitat for parallel computation. We have pursued our investigations of efficient VLSI architectures, suitable for a variety of problems (broad-purpose

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424, and by the National Science Foundation under grants MCS 81-05552, ECS 81-06939, MCS 80-08845, IST 80-12240, and IST 80-12242.

architectures). We have studied in detail an area-time optimal multiplier for very large integers, which has a highly regular layout in the form of a square mesh. In addition, we have begun the exploration of a novel approach to the sorting problem, to be implemented in a significant variant of the cube-connected-cycles, and that offers an area-time performance superior to previously known schemes.

12.3 Layout Theory and Design Aids

A theory of layout of VLSI circuits is a current technological need, since most placement and routing tasks are presently carried out using empirical techniques. We have studied the channel routing problem in some detail. We have determined an algorithm for two-layer routing which bounds both the area and the delay; in particular, the channel width and the maximum wire length are, in some sense, both optimized. We also developed a simple yet effective technique for calculating a lower bound on the number of tracks required to solve a given two-layer channel routing problem. Moreover, we have shown that optimal wiring (i.e., density) is always possible if just three conducting layers are available; we are currently trying to extend this theory to more complex and general channel routing problems.

In addition, we have investigated design problems that profitably use the techniques of computational geometry, in particular of the so-called "geometry of rectangles". In this area, we have developed a search technique for a collection of n parallel segments (as occur in VLSI mask technology), which runs in time O(log n) with an expected storage O(n). We have also developed a general algorithm for the computation of a rectilinear mask expressed as an arbitrary Boolean function of a set of rectilinear masks (papers in preparation).

12.4 Data Structures

Continuing the study of dynamic embeddings between data structures, we devised an optimal on-line simulation of a tree by a d-dimensional array in time O((N**(1+1/d))/(log N)). Within constant multiplicative factors, no faster simulation is possible. The simulation is cast in terms of multihead Turing machines. An information-theoretic argument gives the worst-case lower bound on the time required.

We have also been continuing our investigation into efficient storage and accessing of data for information-retrieval. We have obtained information-theoretic lower bounds (and shown that some of these bounds are achievable) for storage of some simple data structures and the access costs for corresponding operations.

12.5 Foundations of Complexity Theory

We have been studying the properties of "context-free graphs", graphs in which most of the important graph theoretic properties are decidable. Major results were obtained relating such graphs to pushdown automata (papers in preparation).

Also, we have been studying how alternating automata can be used with languages of infinite strings and trees. This subject is closely related to the study of infinite games. The use of such automata yields a new and much simpler proof of Rabin's theorem concerning the decidability of second-order theories.

12.6 Image Processing Algorithms and Architectures

We have studied interleaved pyramid architectures and multiprocessor pyramids for bottom-up image analysis. Current research focuses on achievable throughput in a hierarchical interconnection of processors that compute non-oblivious algorithms. The running times of the algorithms are modeled probabilistically.

13. ADVANCED AUTOMATION

Faculty and Senior Staff

N. Ahuja	G. F. DeJong	L. R. Maran
R. T. Chien	J. Q. Fang	D. L. Waltz
	T. S. Huang	

Graduate Students

N. Bridwell	J. Gibbons	A. Pajerski
D. Chen	W. Ho	Y. Pan
S. Cross	W. Hoff	J. Pollack
R. Dinitz	M. Houghton	J. Porter
M. Dorfman	J. Jones	R. Rajapopalan
D. Farwell	S. Keller	D. Spoor
R. Fletcher	C. Nash	M. Tuceryan
W. Frederick	P. O'Rorke	R. Yen

13.1 Natural Language Understanding*

This project is concerned with judging the plausibility of natural language sentence meanings, with representing meaning and context, and with novel processing mechanisms for natural language understanding.

Progress was made on the understanding and representation of language describing event descriptions, spatial relationships, time, and causality. "Event shape diagrams," a new representation form for dealing with sequences and concurrency of events, were introduced [13.23,13.24]. We are using these and other schemas to capture and represent the intricacies of fluid flow, causality, mechanical relationships, and other properties. To accomplish this, it is important to use hierarchically layered models, representing the same event or mechanism at different levels of abstraction. In addition,

* This work was supported in part by the Office of Naval Research under contract N00014-75-C-0612 and in part by the Air Force Office of Scientific Research under contract F49620-82-K-0009.

there must be separation of complex models at a given level into simpler partial models. Mechanisms for representing and reasoning about such systems are being developed as an extension to event shape diagrams.

Event shape diagrams were used to show some mechanisms for deriving the correct meanings and inferences in metaphorical sentences, such as "John ate up the compliments," or "John's legs ate up the space between himself and Mary." [13.12] We have investigated a feature transfer model for understanding metaphorical language. This model matches the two items being compared in a metaphor, and transfers material from the "vehicle" of the metaphor to the target domain, based on saliency assessments of various features.

We have also been working on a parallel, analog model for knowledge integration and decision-making in the context of natural language processing. The model involves dynamically constructing an unstable weighted network of possibilities, while concurrently sifting and stabilizing the network such that the best interpretation is highlighted. The model has been successfully applied to a natural language processing task [13.21].

13.2 Explanatory Schema Acquisition*

The schema learning project is exploring artificial intelligence techniques that will enable a computer system to learn general world knowledge in the form of "schemas" through its interactions with an external environment. A schema specifies how a particular real world situation is likely to progress and why. To act intelligently in many different situations a system requires a vast number of schemas. The problem of "programming in" large numbers of schemas has greatly limited the intelligent behavior of past AI systems.

A computer system ought to be able to automatically acquire these schemas directly from its experiences much as people do. The world knowledge already possessed by the system is used to generalize individual experiences into schemas. We have devised a taxonomy of the kinds of learning that take place, the conditions in which they can occur, the effects each has on the system's

* This work was supported in part by the National Science Foundation under contract NSF IST 81-20254.

schema memory, and some of the mechanisms by which they can occur. The kinds of learning are: (1) schema composition, (2) secondary effect elevation, (3) schema alteration, and (4) volitionalization.

A computer system to implement and test these ideas is near completion [13.12,13.17,13.18].

13.3 Cognitive Universals*

In order to write natural language understanding programs, it is essential to have good target forms for representing meaning. In this project, we have combined the linguistics and artificial intelligence approaches, in the hope that we can write programs that are better models for human cognitive processing, as well as better computer programs (that is, ones that are more easily extensible and less likely to require radical revision).

One part of this work has focused on roles and role relationships between the real world elements represented by the noun phrases of a given sentence, and the states or events reflected by the verb. We are looking at role-related syntactic, semantic, and cognitive phenomena in several languages. A questionnaire was prepared, and administered to speakers of Spanish, Basque, and Mandarin. The results of the questionnaire should allow us to assess the variety of mechanisms and case role distinctions in a number of languages, so that we can better build proper cognitive distinctions in our computer programs.

We have also been concerned with understanding the reasons why natural languages differ so markedly in their encoding strategies for space-time meaning. We have studied this phenomenon in English, Jinghpaw and Burmese of Sino-Tibetan family of languages, Blackfoot, Cree, Delaware and Ojibwa of the Algonkian family, and Tarascan.

Finally, we are investigating the use of machine-readable dictionaries and thesaurus for building the lexicon for a natural language system.

---

* This work is supported by the National Science Foundation under contract NSF IST 81-17238.

13.4 Hierarchical Control and Monitoring with Conceptual Levels*

This work deals with the use of knowledge-base architecture and planning control mechanisms to perform an intelligent monitoring task in a complex domain.

The domain for our expert planner is the aircraft flight domain. The flight domain knowledge is presently organized into four conceptual levels: the route level, the trajectory level, the flight-control level, and the aircraft subsystem level. The levels constitute a form/function hierarchy which facilitates problem-solving and monitoring. As an example of the form/function relationship, an aircraft route is implemented by a trajectory, which is in turn implemented by a sequence of flight control settings.

The causal framework determines the conceptual levels and the planner at each level only has to consider the variables within the causal framework. The levels architecture allows us to focus attention and also provides the ability to do recovery planning based on a change in the context at any level. This property is unique and desirable in real-world problem-solving.

The work accomplished thus far consists of the design of a semantically oriented planning architecture and an initial design of the inter-level planning-control mechanism. This mechanism performs meta-planning in the levels context. Problems and issues currently under investigation include (1) focus of attention, (2) vertical problem decomposition, (3) planning control, (4) inter-level teleological consistency, (5) domain knowledge representation, and (6) partial planning.

13.5 Mechanism Modeling and Automatic Diagnosis**

Present day diagnosis systems use either table-look-up procedures or production rules for storing the information needed. Neither approach deals with the fact that for a diagnosis system to perform intelligently, it needs to understand the basic principles which are embodied in the design and structure of the mechanism. Because of this weakness neither approach can

---

* This work is supported by the National Aeronautics and Space Administration under contract NASA NCCI-52.

** This work is supported in part by the National Aeronautic and Space Administration under contract NASA NCCI-52, by the Department of Transportation/Federal Aviation Administration under contract FA79WA-4360, and in part by the United States Air Force under contract F49620-82-K-0009.

handle multiple faults effectively.

The purpose of this work is two-fold. First, we will develop models of understanding of mechanisms, about their operating principles, structure-function relationship and hierarchical interaction. Secondly, we shall exploit these mechanism models for intelligently diagnosing multiple faults.

As a typical case study we have developed some initial understanding models for a generic refrigeration system in terms of such concepts as heat-transfer and circulation. With the help of these concepts models we can analyze any schematic of a refrigerator and identify the relevant components which are pertinent to an operation, such as circulation. We can then easily construct the circulation subsystem as an abstraction.

As another typical case study we have established a systematic process for comprehending the working of an amplifier. The essential steps are (1) physical instantiation, (2) semantic template verification, and (3) constraint propagation. With these steps one could analyze novel new structures that fall in the same general category and achieve an understanding of the function/structure relationship at all levels, including the component level, the sub-structure level and the mechanism level.

Finally, in the direction of diagnosis some additional modeling is needed. We developed flow-concept models for initiation isolation, functional models for detailed analysis and constraint models for verification. These models seem to be necessary for a theory of diagnosis based on mechanism models.

13.6 Air Traffic Control, Problem-Solving, and Learning*

The purpose of air traffic control is two-fold. First, we must resolve all potential traffic conflicts. Secondly, we must deliver all aircraft safely to their destinations, in a fuel-efficient manner, with as little delay as possible.

In the jargon of AI we are trying to do problem-solving with conflicting goals. Since there is no existing theory of ATC we have the problem of generating the theory as well as carrying out its computerization. We have decided it would be a good idea to include some learning capabilities in the

* This work is supported by the Department of Transportation/Federal Aviation Administration under contract FA79WA-4360.

expert system we are building. The learning we are attempting is called "advice-initiated learning." Using this type of learning, the system first attempts a solution. The solution is reviewed by an adviser who presumably is an expert in ATC. The adviser either approves the solution or gives advice in the form of a new strategy. The computer then has the task of digesting the advice; in particular, it must figure out why the suggestion is indeed better than its own solution.

13.7 Computer Vision*

Hierarchical organizations of small, general purpose processing elements to perform fast bottom-up image analysis were proposed. Three different architectures were given: Pyramids, interleaved pyramids and pyramid trees. Different architectures exhibit different performances with respect to hardware requirements and operating speed [13.16].

Approaches to dot pattern processing using Voronoi neighborhoods were proposed [13.10]. Segmentations of dot patterns containing homogeneously dense segments were obtained. Experiments on matching dot patterns in the presence of noise were performed.

The problem of generating the three-dimensional occupancy map of a scene from stereo image-pairs was investigated. A three step procedure consisting of obtaining depth map, surface map and a volumetric representation was given [13.15]. Algorithms were developed to update the octree representation of a three-dimensional object as the object undergoes translation and rotation [13.27].

13.8 Image Sequence Processing and Dynamic Scene Analysis**

The processing of images involving motion has become increasingly important. Applications include target tracking, dynamic robot vision, image bandwidth compression, and medical imaging. Image sequence processing involves a large amount of data. However, because of the rapid progress in

---

* This work is supported by the National Science Foundation under grant NSF ECS-81-06008.

** This work is supported in part by the National Science Foundation under grant NSF ECS 81-12082, and in part by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424.

computer, LSI, and VLSI technologies, many useful processing tasks for image sequences can now be performed in a reasonable amount of time. A central issue in dynamic scene analysis is the determination of three-dimensional motion and structure from image sequences.

Uniqueness conditions for estimating 3-D motion parameters from two frames were obtained [13.22]. Progress was made in determining models for 3-D motion estimation problems [13.25]. We also developed efficient algorithms for finding corners in 2-D pictures [13.20]. Applications to stereo pair matching and motion estimation were presented [13.19]. Some techniques for image recognition by matching relational structures were developed in [13.20]. A simple procedure was developed [13.11] to generate the minimum depth surface description of a three-dimensional scene that is consistent with a series of images from a laterally translating camera.

14. INFORMATION RETRIEVAL

Faculty and Senior Staff

L. W. Lannom C. G. Robins L. C. Smith
S. E. Preece M. E. Williams

Graduate Students

J. Mendoza C. Tenopir S.-C. Wang

14.1 Introduction

During the 1981-1982 time period, we conducted in information retrieval a number of research and development projects and participated in the University of Illinois' online search service. Major activities included analysis of database data; a test of the feasibility of automatically determining the overlap between bibliographic databases; development of a computer-readable databases directory; and participation in the University of Illinois' online search service.

14.2 Analysis of Database Data*

Our staff maintains a body of information about commercially available databases called the Database of Databases. We have continued to study various statistical characteristics of this population based on the material in our database. Such statistics and analyses are useful both to researchers in the area and to the users and producers of databases.

The particular information developed in the studies performed in the last year considered the age, size, type (scientific, medical, etc.), and source (government, private, etc.) of the databases covered. At present, 773 databases are covered by our Database of Databases, but any given study might include only a specified subset of those depending on the needs of the study. The most recent analyses are for the years 1980 and 1981.

---

* This work was supported by the University of Illinois

The software used in this research consisted of a program framework containing slots into which logic could be inserted to perform specific data selection, cleanup, and analysis. The data was first extracted from the database by our data access program, USER, and written into a file of (tag, value) pairs. The analysis programs read that file and selected the tags of interest. An effort was made to overlap multiple analyses by re-using data selected and cleaned for prior use.

Cross tabulations were made based on defined groupings or actual values, depending on the data involved. Thus, cross tabulations were done involving both raw year of origin versus grouped size and grouped year of origin versus grouped size. Statistical summaries included means, ranges, and standard deviations of raw data and correlation coefficients between raw data and grouped data. Detection of bad data included identification of records containing illegal or missing values.

The work involved in this project also developed a framework for further studies of the databases available to researchers today. We are currently updating the database and improving the coverage and consistency of data fields that are likely to be important in future studies.

14.3 Federal Emergency Management Agency Database Requirements Assessment and Resource Directory Model*

We identified and analyzed word-oriented (bibliographic, textual, directory, etc.) databases relevant to various units within the Federal Emergency Management Agency (FEMA).

The use of computer databases instead of manual searching saves time, an important factor in emergency situations. Computer databases usually provide more timely information and allow one-step searching of complex topics tailored to meet individual needs. A directory indicating which databases contain information of interest to FEMA would be a valuable resource for all FEMA units. This project developed a methodology for compiling such a directory and also provided a model as a sample directory.

Databases of potential relevance to FEMA were identified and, after

---

* This work was supported by the Federal Emergency Management Agency under grant EMW-1-4058.

discussion with FEMA personnel, the fifteen judged to be most relevant to the most FEMA areas of interest were selected. Subject profiles that reflect the interests of all individual FEMA units were developed in conjunction with appropriate FEMA personnel. Profiles were used to test the fifteen databases online. The databases were ranked by subject coverage, amount of information, and type of information based on the online search results. We created a sample FEMA Database Directory based on the analysis of the fifteen databases and including samples of citations from each database.

Directory of Computer-Readable Bibliographic Databases*

The Computer-Readable Bibliographic Databases - A Directory and Data Sourcebook, compiled and edited by Professor Martha E. Williams and Sandra Rouse, was published in 1976 by Knowledge Industry Publications, Inc. Updates to the Directory were issued in April, 1977 and April, 1978. A second edition, including data that was relevant as of December, 1978, was published in Autumn, 1979. A new edition appeared early in 1982, based on the most recent updating of the underlying database. The current edition covers 773 databases.

Data Collection

1. Database processors in Europe and North America were contacted by mail for information on the databases they provided access to.
2. The questionnaire designed for the last directory was revised to achieve a more consistent format. A turnaround questionnaire was computer-generated, containing the information in our files for the databases covered by the last directory. Existing data entries needed only to be verified or changed and missing information supplied by the database producer.
3. The questionnaires were mailed to the database producers and U. S. and Canadian producers were subsequently contacted by telephone for verification of the data and assistance with questions they might have.

---

* This work was partially supported by Knowledge Industry Publications, Inc.

4. Information on the availability of new databases was obtained from the published literature and contacts with database processors/producers. The producers of new databases were interviewed first by phone. The completed questionnaire was then mailed to them for verification and, if necessary, followed up by telephone.

5. Returned questionnaires were checked and data entries standardized.

Data Entry

1. Data was entered online into the Database of Databases file using a preformatting program on an Alpha Microsystems microcomputer. Entries were then printed out, verified, and corrected and edited online as necessary using the DBEDIT program.

Organization

The Directory is organized alphabetically by database name and includes an introduction and four indexes: Subject Index, Database Name/Acronym/-Synonym Index, Producer Index and Processor Index.

Information on each database follows the general format:

1. Basic Information

2. Producer/Distributor/Generator Information

3. Availability and Charges for Database Tapes

4. Subject Matter and Scope of Data on Tape

5. Subject Analysis/Indexing Data

6. Data Elements Present on Tape

7. Database Services Offered

8. User Aids Available

Production

The Directory was formatted for printing using our software and printing masters produced on a Xerox 9700 printer. All indexes were then generated automatically from the database and typeset similarly.

14.4 University of Illinois Online Search Service

The Online Search Service is a service provided for students, faculty, and staff of the University by the Library and our group. Information retrieval services are provided by accessing computer-readable databases from the following search systems: Bibliographic Retrieval Services, DIALOG Information Systems, New York Times Information Bank, System Development Corporation, and the National Library of Medicine.

In addition to serving as one of the locations where searches are conducted, we contribute to the Service by providing monthly financial and usage reports to the Library administration and by providing expert advice in the use of information retrieval services. The financial and usage reports are generated by internally produced software on an Alpha Microsystems microcomputer and are based on accounting data provided by the online vendors and the Library.

14.5 Database Analyses*

We are conducting ongoing analyses of the MARC database. This work involves processing the annual files distributed by the Library of Congress and generating a detailed statistical analysis of the rate of occurrence and size distribution of each field of the records. The resulting tables, which have appeared in the Journal of Library Automation, show for each field (1) the percentage of records in which it appears, (2) the rate of occurrence within records where it appears, and (3) the length of the field in characters. For (2) and (3) we report average, minimum and maximum values and standard deviations.

The distribution of records in Dewey and Library of Congress classes is also reported along with average record lengths for each class. Summary

---

* This work is supported by the Council on Library Resources.

statistics are also listed separately. Finally, we report the changes between reporting periods (showing, for instance, which fields are used more now than at the last report).

We have also begun a second project using the same computer programs to analyze the CONSER database for the Council on Library Resources.

This data allows users of the databases to optimize their applications for the actual characteristics of the databases.

14.6 Automatic Detection of Database Overlap*

This research program addresses the problem of overlap coverage of journal articles among multiple databases. Overlap leads to duplicative processing of material by database producers; duplicative processing and storage of material by online and batch vendors of database services; and retrieval of duplicative material by users of databases. The net result is reflected in costs associated with the databases and an unnecessary expenditure of time on the part of users.

The true extent of the problem is unknown. Several studies have addressed the question of journal coverage overlaps, some have addressed the question of article overlaps in narrow subject areas, and one has attacked the problem of identifying maximum possible overlaps among specific databases. None has studied the problem of determining the actual overlaps among database services.

We are developing a methodology for automatically determining overlap among databases and testing and implementing this methodology on nine databases: AGRICOLA, BIOSIS Previews, CACon, Commonwealth Agricultural Bureaux (CAB), Engineering Index, Excerpta Medica, Inspec, Medline, and Science Citation Index (SCI). The methodology involves analysis of the databases to determine the data elements present in and common to multiple databases to determine effective keys for matching records in multiple files. The matching process will be done in at least two passes. The first pass, or broad screen, will use a match key with high discrimination power to identify candidate duplicate records. A set of finer screens will be used for verifying pairs of

---

* This work is supported by the National Science Foundation under grant NSF IST 79-21018.

records as duplicates. The second pass may employ Harrison keys (which are bit string representations of titles) and Hamming distance techniques (for overcoming slight variations in representation of titles) together with matches on other elements as needed.

Results will be tested: (1) by using manual verification of a statistically representative sample in order to determine mismatches, and (2) by using a known set of duplicate records to see if they are identified by the screens. The evaluation in terms of mismatches (wrong matches) and missed matches will provide a measure of the effectiveness of the techniques. Further evaluation in terms of gross costs will be carried out in order to determine the efficiency of the techniques.

The study will produce overlap statistics among nine databases, data element frequency statistics, and a methodology for duplicate detection that might be used by database producers or database vendors. The resultant methodology could be used as a preprocessing step to reduce storage and processing costs or as a post-retrieval step to eliminate the duplicative output delivered to users.

During the second year of the project, tapes have continued to arrive from the database producers, covering the 1978-1979 period. Sample subsets have been read and preliminary planning for the file structures and processing flow has been done. The contents of the samples have been studied statistically to identify data elements useful in the matching process and to allow estimation of storage requirements. The software has been ported from the DEC System/10 to the DEC VAX 11/780 and further samples have been read and evaluated preparatory to performing large-scale conversions.

15. COMMUNICATIONS

Faculty and Senior Staff

T. Basar	R. J. McEliece	D. V. Sarwate
T. U. Basar	H. V. Poor	E. Szilléry
B. Hajek	M. B. Pursley	S. Tantaratana

Graduate Students

B. Aazhang	J. S. Lehnert	M. S. Schmidt
A. C. Blumer	J. Martersteck	C. M. Stadler
C.-I Chang	M. Nayeri	W. E. Stark
P. Enge	R. G. Ogier	K. S. Vastola
F. D. Garber	T. J. Pavlik	S. Verdú
E. A. Geraniotis	G. Sasaki	M. S. Wallace
S. M. Krone		R. Wolf

15.1 Multiple-Terminal Digital Communications*

This is a major research area which includes various problems in spread-spectrum communications and random-access communications networks. The topics that were investigated during the past year include the performance of spread-spectrum multiple-access communications systems, the effects of fading on spread-spectrum communications, communications in the presence of jamming, error-control coding for multiple-access systems, conflict resolution in random-access communications systems, packet radio communications systems, and routing algorithms for communications networks. Progress in this research is described in the subsections that follow.

---

* This research was supported by the Army Research Office under contract DAAG29-81-K-0064, by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424, by the Naval Research Laboratory under contract N00014-80-C-0802, and by the Defense Advanced Research Projects Agency under contract MDA 903-82-C-0026.

15.1.1 Spread-Spectrum Multiple-Access Communications Systems

We have completed the development of bounds and approximations for the average probability of error in direct-sequence (DS) spread-spectrum multiple-access (SSMA) communications systems, and the results have been published in the IEEE Transactions on Communications special issue on spread-spectrum communications. The bounds, which are presented in [15.30] are best suited for SSMA systems with few simultaneously-active transmitters. Since both upper and lower bounds are derived, approximations can also be obtained from these results. For SSMA systems with a large number of simultaneous transmissions, the bounds are difficult to evaluate, but the approximation developed in [15.9] can be applied. This approximation is based on the integration of the characteristic function of the multiple-access interference, and its computational requirements increase only linearly in K, the number of simultaneous transmissions. The methods developed in these two papers have proved to be extremely useful in the study of DS/SSMA and hybrid SSMA systems.

An investigation of the effects of partial correlation on the performance of DS/SSMA systems was also completed during the reporting period. Some of the results of this study are presented in [15.58]. Our investigation has primarily focused on systems for which the number of chips per bit, N, and the period of the signature sequences, p, are relatively prime numbers (this is usually the case in practical systems if $p > N$). In this case we find that the resulting loss of control of the sequence phases leads to an increase in the multiple-access interference over that present in a DS/SSMA system which has one data bit per period (i.e., $p = N$) and employs the signature sequences in their optimal phases.

We have considered the design of quadriphase sequences with good correlation properties. We are able to construct a set of $N + 1$ sequences of period N (where N is a multiple of 4 and $N + 1$ is a prime power), for which the correlation parameter θ_{max} is upper bounded by $3(N+1)^{-1/2}$. We can also enlarge this set to have $2(N+1)$ sequences with an upper bound on θ_{max} of $3(N+1)^{-1/2} + 5$. Experimental results show that the bound is actually quite weak.

An investigation of the performance improvements achievable by use of error-control coding has also been initiated, and preliminary results are

presented in several recent papers (e.g., [15.56,15.59,15.61]). The general conclusions are that error-control coding is extremely beneficial in nearly all communication environments, and it is absolutely necessary for acceptable bit error rates in frequency-hopped spread-spectrum communications in the presence of jamming, fading, or multiple-access interference. Coding gains of 20 to 30 dB are common in such systems.

15.1.2 Spread-Spectrum Communications for Packet Radio Networks

Because of the severe specular-multipath fading that arises in urban areas, we have investigated the effects of such fading on the performance of direct-sequence spread-spectrum communications. Results for both coherent [15.46] and noncoherent [15.47] receivers have been published. Although these results are for receivers which utilize standard matched filters, work is also in progress to evaluate the performance of direct-sequence spread-spectrum communications via specular multipath channels when post-detection integration or RAKE-type filters are employed in the receiver. Of particular interest is the performance of receivers with post-detection filtering when employed on channels with jamming and multiple-access interference.

In addition to the research on direct-sequence spread spectrum, we are also pursuing a parallel investigation of frequency-hopped spread spectrum for packet radio networks. It appears that for channels with partial-band jamming or multiple-access interference, frequency-hopped modulation in conjunction with error-control coding provides a very robust system. It seems at this point that the tradeoff is between the anti-multipath capability of direct-sequence spread spectrum and the anti-jam and multiple-access capabilities of coded, frequency-hopped spread spectrum. Of course, error-control coding is also useful in a direct-sequence system, but for many types of interference (e.g., multiple-access interference) the amount of interleaving required in direct-sequence systems may be prohibitive. Furthermore, coding cannot take care of the problem of unequal power levels (i.e., the so-called "near-far problem") in a packet radio network.

15.1.3 Coding, Modulation, and Routing for Communication Networks

This research area includes several related topics that arise in

communication networks which must operate in the presence of jamming, fading, and multiple-access interference. The topics include frequency-hopped spread-spectrum communication via fading channels, communication in a hostile jamming environment, and routing in communications networks. Progress in research on these topics is summarized in the three paragraphs that follow.

Our work on slow-frequency-hopped spread-spectrum communications systems is concerned with the probability of error for such systems when operating in the presence of fading, multiple-access interference, jamming, and other radio-frequency interference (RFI). Various types of fading have been considered including selective and nonselective Rayleigh and Rician fading. We have also investigated the performance of error-control coding (particularly burst-error-correcting coding) for frequency-hopping spread-spectrum systems. One of the most promising coding schemes that we have investigated utilizes Reed-Solomon codes with partial interleaving for slow-frequency-hopping (more than one code symbol per hop) or Reed-Solomon codes and diversity for fast-frequency-hopping (one code symbol per hop). Results are published in several recent papers including [15.9,15.41,15.44, 15.59,15.60].

In related work, we have derived the optimum receiver for a fast-frequency-hopping scheme proposed for mobile radio applications, and obtained bounds on the error probability for a suboptimum receiver which is easier to implement than the optimum receiver. These bounds have been compared with simulation results on error probability for the originally-proposed suboptimum receiver. It is found that the new receiver structure is superior to the original one.

In the area of communication in the presence of jamming, our research has focused on information-theoretic fundamentals. We formulated a two-person, zero sum game with mutual information as the payoff function. The players in this game are the jammer and the coder. By solving the game, one first finds saddlepoint strategies which indicate the general kind of jamming/anti-jamming strategies the real players ought to use in practice. The work has continued and several saddlepoints have been calculated. Also, the performance of several explicit coding schemes have been evaluated in the presence of optimal jammers. In a related area we undertook a serious study of the relative merits of interleaved vs. un-interleaved coding schemes in the presence of

general interference phenomena, including jamming, fading and other RFI.

A main result of our research in communication network analysis during this period has been to obtain bounds on the delay incurred in a buffered station with an arbitrary packet arrival process. This bound applies to stations within a network under dynamic, non-feedback routing strategies. A rather sharp bound was also obtained for the delay incurred in a station when the traffic is obtained from a generalized round robin fanout of a Poisson traffic stream.

Recently we have also obtained a new characterization of optimal dynamic routing strategies for interacting queues with state feedback information. In the coming year we expect to complete a unified performance analysis of optimal and efficient suboptimal dynamic routing strategies for packet communication networks both with and without state feedback information.

15.1.4 Random Access Techniques for Communication Networks with Frequency Hopping

This research is primarily concerned with basic random access techniques which are appropriate for mobile packet radio networks with frequency hopping. Two key features of such networks which impact random access protocols are first that channel feedback is severely limited and second that frequency modulation in itself yields a multiple access capability which should be exploited. We have introduced new dynamic retransmission control schemes and have shown their suitability in a frequency hopping environment. This work included identifying possible feedback information and determining how it could be used to achieve stable throughput in spite of a fluctuating demand. Other suitable random access strategies which require only acknowledgement feedback have also been studied.

More realistic models of stations which include time-varying packet generation rates have been considered in conjunction with random access schemes. So far exact analysis of TDMA and perfect scheduling protocols have been achieved using matrix iteration methods.

Certain aspects of mobile network organization have also been considered. We have discovered how differential transmission radii in different frequency bands can be exploited to increase network throughput and decrease multiaccess interference. We have proposed and analyzed methods whereby traffic can be

efficiently distributed among available time or frequency slots in a decentralized way to achieve balanced loads with reduced traffic variance. Finally, centralized and decentralized algorithms have been obtained for open-loop optimal dynamic routing in communication networks modeled by pure flow equations. The algorithms appear to be feasible to implement in much larger networks than previously known optimal dynamic routing algorithms.

15.2 Signal Detection, Estimation, and Filtering*

The overall purpose of this research effort is to develop effective statistical signal processing procedures for applications in communications and control. Specific areas currently under investigation include the development of robust detection, estimation and filtering procedures for operation in uncertain statistical environments, the study of techniques for efficient digitization of signal detection systems, and the analysis of multistage decision processes. Progress in these areas is described briefly in the following subsections.

15.2.1 Robust Signal Processing in Uncertain Statistical Environments

In general, the area of robustness deals with the design of systems and procedures which are relatively insensitive (in terms of performance) to small deviations from an assumed model. Robust techniques are of interest in a wide variety of applications including radar, sonar, and seismology, inasmuch as inaccurate models are the norm for such situations; and robustness has been studied widely in the contexts of communications, control, and inferential statistics. The basic assumption for the analytical study of robustness in detection and filtering is that the statistics of signals and/or noise are not known exactly, but rather are known to be within some (usually nonparametric) classes representing uncertainty in the underlying model. The primary technique for designing a robust system is to seek a system achieving the best worst-case performance over the relevant uncertainty classes; i.e., the primary design philosophy is minimax. Within this context several detection,

* This research was supported by the Army Research Office under contract DAAG29-81-K-0062, the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424, the Office of Naval Research under contract N00014-81-K-0014, and the National Science Foundation under grant ECS-79-16453.

estimation and filtering problems have been considered under this project, and these are described in the following paragraphs.

One area in which several minimax and robustness results have been obtained is that of state estimation and control for linear dynamical systems with uncertain statistical behavior. In particular, minimax results have been developed for steady-state linear estimation [15.29] and control [15.20,15.53, 15.54] of time-invariant systems and for finite-interval estimation and regulations [15.63,15.67] of time-varying systems. Also, an algorithm for the state estimation of such systems with random jump inputs has been developed and is described in [15.4]. Along these same lines the problem of robust filtering and smoothing of stationary processes with uncertain spectra has also been considered. Specific results include a characterization of minimax smoothers for homogeneous random fields with spectral measures known only to lie in general uncertainty classes generated by Choquet capacities [15.24], an analysis of the effects on performance of spectral uncertainty on stationary linear filtering [15.34], and a study of minimax filtering for observed Poisson processes with uncertain rate characteristics [15.44,15.45]. Two related studies include a characterization of the MSE rate-distortion function for information sources with uncertain spectra lying in capacity classes [P10] and the development of jam/antijam strategies for data transmission through the Gaussian test channel with an intelligent jammer [15.5,15.37].

Another aspect of robustness in which several results have been obtained recently is that of robust signal detection. Specific results in this area include the development of robust detectors for the (nonlinear) detection of signals in additive dependent noise with uncertain first-order distribution [15.28], a study of the discrimination of point processes with uncertain rate functions [15.45], the design of matched filters for digital transmission through uncertain channels [15.36,15.65,15.67], and the characterization of robustness in the quadratic receiver design problem [15.64,15.67]. Also, [15.19] considers a design technique known as the segment method as an alternative to minimax for designing binary decision systems within uncertainty.

In addition to the above specific results, a general study of the characterization of solutions to minimax robust design problems is reported in [15.64,15.67]. The techniques developed here allow the unification and

generalization of many previously studied robustness analyses as well the extension to new design problems. Also during this reporting period several survey papers on robustness topics have been prepared [15.18,15.51,15.57]. The topics of these surveys include robust signal processing for communication systems [15.18], robust filtering [15.51], and the use of distance measures in robust detection and discrimination [15.57].

15.2.2 Digital and Multistage Signal Detection Systems

In addition to the robustness work surveyed in the above subsection, several other aspects of the design and analysis of signal detection systems have been considered recently. Progress in this area is described briefly in the following paragraphs.

One area in which recent progress has been made is that of designing efficient systems for detecting signals in dependent non-Gaussian noise backgrounds. For example, optimum detection of signals in weakly dependent noise is considered in [15.27]. It is shown here that, for a moving-average dependence model, efficient detection can be achieved by reshaping the independent-noise optimum detection nonlinearity with an additive linear correction term. An investigation of several commonly used noise models indicates that the resulting performance improvement is most significant for impulsive types of noise. In [15.17] similar modified structures are considered for detecting signals in ϕ-mixing noise. It is demonstrated that the ϕ-mixing model with only the mixing coefficients given is not sufficiently descriptive of dependence structure to admit a design which is uniformly better than the independent-noise design. (This is in contrast to the moving-average model of [15.27].) However, optimum memoryless designs for ϕ-mixing and other dependence models can be derived using general results of [15.25] provided that the second-order distributions of the noise-process are known. The optimum system in this case is the solution to a Fredholm operator equation of the second kind and, as such, can be characterized in terms of the Barrett-Lampard expansion of the noise process.

A second area of recent interest is that of analyzing the efficiencies of multistage detection procedures. Two basic types of procedures have been studied in this context. In [15.66], a useful class of multistage binary hypothesis tests is proposed and analyzed. These tests operate by testing an

initial sample and then taking additional samples if the first sample indicates rejection of a particular one of the hypotheses. It is seen that significant efficiency can be gained (over fixed-sample-size procedures) by doing this if one of the hypotheses is rare (as in the case, for example, in search radar). A nonparametric version of this procedure is discussed in [15.33]. In [15.32], the (Pitman) efficiencies of truncated Wald sequential tests are analyzed. These tests, although known for some time, have not been analyzed previously in this manner. This analysis clearly indicates the favorability of truncation in such situations, particularly when very small error probabilities are desired.

Finally, some related work includes a numerical study of the convergence behavior of the relative efficiencies of some commonly used detection systems [15.23], and a correct derivation of the output signal-to-noise ratio for quadratic receivers and fading channels [15.35] which previously had been incorrectly derived in the literature.

16. ANALOG AND DIGITAL CIRCUITS

Faculty and Senior Staff

E. I. El-Masry	Y. Li	W. Mayeda
I. N. Hajj	M. R. Lightner	T. N. Trick
W. K. Jenkins	L. Mao	M. E. VanValkenburg

Graduate Students

N. Attaie	D. Hocevar	V. Rao
W-K. Chia	C. N. Lam	J. Stothoff
R. Davis	N. Nguyen	V-P. Wei
P. Embree		C-P. Yuan

16.1 Hierarchical Design Aids for VLSI Circuits*

This work covers two related topics in the area of design verification for VLSI circuits. One topic is concerned with logic expression extraction from the circuit layout or the interconnection description, and the other topic is concerned with the development of fast and relatively accurate methods for timing simulation.

In the design verification process of VLSI circuits it is often desirable, or even necessary, to obtain symbolic Boolean expressions at specified nodes in the system from the extracted circuit description. The extracted logic description can then be compared with the original logic specifications to verify the design. This verification, in fact, should be carried out before any circuit or timing simulation is performed. Extracted logic expressions can also be used to describe parts of the system for mixed-mode simulation [R1] or could be evaluated using ternary algebra for switch-level [R2] or multiple-delay simulation [R3].

In our research work, an approach for generating logic expressions at

---

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under Contract N00014-79-C-0424.

specified nodes in MOS circuits has been developed. The approach is based on partitioning the circuit into "one-way" subcircuits and then using path finding algorithms to generate logic expressions at the subcircuit level. Composite expressions are then generated by interconnecting the subcircuits. The approach has been successfully implemented in a computer program which can generate logic expressions of extracted or specified circuit descriptions. In addition, the program is capable of performing switch-level simulation for given input logic sequence specifications.

In the area of timing simulation a new approach has been developed. The approach is based on a modified Gauss-Seidel-Newton method for solving the partitioned circuit equations. When feedback paths exist in the circuit, a predictor formula is used to estimate the state of the "yet unsolved" subcircuits. It has been found that the new approach gives more accurate results than existing Gauss-Seidel methods, such as the one used in MOTIS-C [R4], without requiring much additional computation. The approach has been implemented and tested in a computer program for simulating MOS circuits. The program also includes procedures for analysis sequencing, feedback detection, and an input/output subcircuit scheduler which schedules only those subcircuits that affect the output directly or indirectly.

In order to further improve the speed of timing simulation, a new approach to multiple-delay logic simulation is under investigation. Circuit simulation is used to determine the propagation delay as a function of the rise and fall times of the input signal and the loading on the circuit for a given technology. This information is stored in a table. Scaling techniques can be used to compensate for different sized transistors. Simulation results from combinatorial circuits indicate a close match between the signal waveforms obtained from circuit simulation with the program SPICE and those obtained from a three level multiple-delay logic simulator which uses the above table look-up and scaling techniques [16.26].

16.2 Switched-Capacitor Filters - Structures and Statistical Design*

Research on switched-capacitor (SC) filter design techniques has resulted

---

*This work was supported by the National Science Foundation under Grant ENG 78-11758.

in new SC structures which can be implemented basically in two different ways, either by using SC first-order building blocks or SC biquads. These structures are the state-space (SS) [R5-R9,16.21,16.27], the multiple-input follow-the-leader feedback (MIFLF) [R10,R11], and the inverse follow-the-leader feedback (IFLF) [16.10,16.11]. Theory and procedures for the optimum implementation of these types of SC filters have been developed.

The sensitivity of the transfer function of the IFLF circuit with respect to the capacitance ratios is surprisingly low as compared to other low-sensitivity SC structures, such as the bilinear ladder [R11,R12]. As compared to the MIFLF, the IFLF has lower passive-sensitivity and higher active-sensitivity. The MIFLF active-sensitivity is also lower than that of the bilinear ladder [R12].

In the area of statistical circuit analysis and design, several variance reduction techniques have been studied with respect to their application in estimating circuit yields. It has been shown that given an approximation of the region of acceptability with a given accuracy, importance sampling techniques deteriorate rapidly as the dimensionality of the parameter space increases. However, modest reductions in the variance of the yield estimator can be obtained with stratified sampling techniques. Also, a practical method has been proposed for the implementation of the control variate method. This method may be the most useful in a general purpose statistical circuit analysis program. Finally, a new approach to Monte Carlo based yield maximization has been investigated. In a variety of passive, active, and switched-capacitor filter circuits, it has been shown that a quadratic model can be used to approximate the responses over a parameter grid several standard deviations in length. Thus, the circuit yield for different design values can be estimated using correlated sampling and the quadratic model. This method is very efficient if line search techniques are used to find the maximum yield along a given search direction. Several filter examples show that the global behavior of the quadratic model is good and that it is very effective for yield maximization [16.24].

REFERENCES

[R1] A. R. Newton, "The simulation of large-scale integrated circuits," ERL Memo No. ERL-M78/52, University of California, Berkeley, 1978.

[R2] R. Bryant, "MOSSIM: A switch-level simulator for MOS LSI," Eighteenth Design Automation Conf., ACM, pp. 786-790, June 1981.

[R3] H. N. Nham and A. K. Bose, "A multiple delay simulator for MOS LSI circuits," Seventeenth Design Automation Conf., ACM, pp. 610-617, June 1980.

[R4] S. P. Fan, M. Y. Hsueh, A. R. Newton, and D. O. Pederson, "MOTIS-C: A new circuit simulator for MOS LS circuits," IEEE International Symposium on Circuits and Systems, pp. 700-703, April 1977.

[R5] N. Attaie and E. I. El-Masry, "Optimum realization of switched-capacitor filters," Proc. of the 23rd Midwest Symposium on Circuits and Systems, pp. 433-438, Toledo, OH, Aug. 1980.

[R6] E. I. El-Masry, "State-space switched-capacitor filter structures," Proc. of the Fourteenth Asilomar Conf. on Circuits, Systems and Computers, Pacific Grove, CA, November 1980.

[R7] E. I. El-Masry, "Design of switched-capacitor filters in the biquadratic state-space form," Proc. of the 1981 IEEE ISCAS, pp. 179-182, April 1981.

[R8] E. I. El-Masry, "Strays-insensitive state-space switched-capacitor filters," submitted to the IEEE Trans. on Circuits and Systems (Revised April 21, 1982).

[R9] E. I. El-Masry, "Strays-insensitive active switched-capacitor biquad," Electronics Letters, vol. 16, no. 12, pp. 480-481, June 1980.

[R10] N. Attaie and E. I. El-Masry, "Synthesis of switched-capacitor filters in the multiple-input follow-the-leader feedback topology," Proc. of the 1981 IEEE ISCAS, Chicago, IL, pp. 175-178, April 1981.

[R11] N. Attaie and E. I. El-Masry, "Multiple-loop feedback switched-capacitor structures," submitted to the IEEE Trans. on Circuits and Systems (Revised June 9, 1982).

[R12] M. S. Lee, G. C. Temes, C. Chang and M. B. Ghaderi, "Bilinear switched-capacitor ladder filters," IEEE Trans. on Circuits and Systems, vol. CAS-28, pp. 811-821, Aug. 1981.

17. DECISION AND CONTROL

Faculty

T. Basar	P. V. Kokotovic	P. W. Sauer
J. B. Cruz, Jr.	D. P. Looze	N. Wax
	W. R. Perkins	

Research Associate

B. Avramovic

Graduate Students

R. Amir	M. Gollakota	P. F. Parent
J. Benhabib	P. Ioannou	G. Peponides
D. Cansever	B. Krogh	V. Saksena
Y. M. Chan	D. K. Lindner	H. Salhi
J. C. Darragh	R. McEwen	H. Tharp
J. S. Freudenberg	R. Milito	J. Wen
D. Gahutu		P. West

17.1 Control and Decision Strategies for Systems under Imperfect Information*

Uncertainties arise because of unknown system parameters, unknown signal environments, and hardware tolerances. Related complexities arise in situations involving multiple system performance criteria and multiple decision makers. The objective of this project is to gain a basic understanding of the behavior and control of complex systems. During the past year, attention has been given to several topics. Highlights are summarized in the following.

An important issue in the design and analysis of control and estimation

---

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under contract N00014-79-C-0424.

systems is the maintenance of system performance in the presence of the inevitable differences between the design model and the true physical system (see [17.14] for a review of robustness and sensitivity results for nonlinear systems). We have addressed this issue using three distinct approaches.

The first approach continues our work on the analysis of feedback properties using measures of gains of various loop transfer functions. For linear systems, useful measures of gain are the singular values of the transfer function matrix. One drawback to singular value analysis is that the singular values must be evaluated at the true plant (as opposed to the nominal design model) to provide a valid indication of certain feedback properties. To circumvent this difficulty, the singular value sensitivity function was developed in [17.56,17.16] as an analysis tool which complements the singular value analysis.

The second approach to robustness problems in estimation and control uses a minimax formulation. The basic idea is to model plant uncertainty by assuming that the true plant is known only to be an element of a given set. The estimator or control system design is then chosen to minimize the worst case performance. Minimax problems of this type were solved for linear estimation [17.32] and control [17.64,17.29,17.65] problems for stochastic systems with white noise processes whose spectral densities are uncertain, and for scalar measurement noncausal linear estimation problems with noise processes whose second order statistics are uncertain [17.54,17.15].

The final approach to robustness problems assumes that the plant is one of a finite number of given models. A cost functional is defined for each model, and the controller structure is fixed. The controller parameters are chosen to minimize a weighted sum of the objective functionals. Although this procedure is not novel, previous solution algorithms have required that an initial stabilizing value for the controller parameters be available. In [17.26], a three level optimization algorithm was developed which eliminates this problem.

In the area of fundamental system theory basic to control strategy development, "strange attractors" have been investigated. Currently there seems to be no unanimity about the definitions of the terms "strange attractors" or of "chaotic behavior" as applied to the solutions of deterministic differential equations. Perhaps this lack of agreement arises

because there are important differences in the behavior of solutions which superficially appear to be similar. We have done a number of calculations to test this possibility; we have computed solutions of a variety of differential equations which exhibit "chaos", including (a) the Lorenz system [R1], (b) Veda's variant of the forced Duffing equation [R2], and (c) several different examples of an autonomous nonlinear feedback system, one such being the system proposed and studied by Sparrow [R3]. Next we intend to study the system recently investigated by Orszag and McLaughlin [R4]; we think their example will be particularly useful as they have computed the long-term correlations for their solutions.

We have found it useful, in comparing the solutions of these different systems, to employ the Lorenz mapping [R1], that is to plot the next succeeding local maximum versus the immediately preceding local maximum of any component of the (vector) solution. (One obtains, for the Lorenz system itself, a sharply cusped inverted "vee".) We have found that some of the solutions exhibited the "vee" and others did not. One would expect that purely random behavior of a solution would yield scatter in the plot, and not a well defined curve.

In nonlinear systems, the tracking or synchronization of a nonlinear feedback system to multiple quasi-periodic inputs has been obtained using both averaging and perturbation methods. One is able to compute the tracking range, at least approximately, in this fashion. These results will be compared with computer generated numerical solutions. Finally, a new proof for the existence of periodic solutions of the generalized Liénard equation has been found.

Major progress also has been made in control of singularly perturbed systems. A composite slow-fast control is designed in two stages to guarantee stability and near-optimality of nonlinear deterministic systems. This result has been generalized to a class of stochastic control problems.

17.2 Implementation Constrained Decomposition and Hierarchical Control*

In large-scale systems, control tasks may be decomposed and hierarchical

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

levels may be imposed on the basis of analytically derived strategies. This project is devoted to the fundamental problem of investigating an analytical framework for incorporating realistic constraints of a computer network. Questions concerning information flow, time scales, and loss of feedback loops are examined in coordinating the multiple controllers in a network.

A decomposition methodology was developed in [17.28] which allows the structure and local convergence properties of iterative hierarchical algorithms to be analyzed. This methodology was applied in [17.27] to analyze decompositions of weakly coupled systems, and in [17.66] to study the effects of problem simplification on the convergence properties of hierarchical algorithms. The results on weakly coupled hierarchical algorithms were used to analyze the convergence of several solution algorithms for the extended algebraic Ricatti equation [17.67].

Another area of investigation concerns Stackelberg games and incentive design. Stackelberg games constitute an important class of multi-person multi-criteria decision problems wherein there is a hierarchy in decision making, some players being in a position to announce their policies ahead of time and enforce them on the remaining players. When the underlying decision process is dynamic such game problems become mathematically challenging, since the standard available techniques and approaches of optimization and optimal control theory are not directly applicable. This part of the project is directed towards developing indirect approaches and a general theory for the solution of such decision problems. During this reporting period we have made important advances in this area, which are summarized in the sequel.

Our first set of results is concerned with the derivation of bounds on the performance of the leader (decision maker at the top of the hierarchy) in deterministic discrete and time dynamic games with two [17.7] or more [17.8] levels of hierarchy; and these bounds have been shown to be tight in many instances [17.6,17.7,17.2]. Derivation of such bounds have also been extended to continuous-time dynamic games for the case when the leader has access to sampled state information [17.44].

Our second set of results is concerned with the derivation of policies (control laws) for the leader that achieve these bounds. In this regard, a set of very appealing affine policies has been obtained, and their existence has been established for a rather general class of such dynamic games [17.41].

In a more recent work [17.52], we have investigated the relationship between such decision problems and incentive design problems that arise in economics, and have also introduced a new concept, viz. least sensitive (robust) incentive policies in problems with parametric uncertainties.

Yet another set of results obtained in the scope of this project involves stochastic Stackelberg games and stochastic incentive design problems. In [17.5] we have obtained the complete solution of a class of continuous-time stochastic Stackelberg differential games by solving a stochastic control problem of a nonstandard type. In [17.48] we have studied the derivation of optimal incentive schemes in two-agent stochastic decision problems with a hierarchical decision structure, in a general Hilbert space setting, with the underlying information pattern allowing the leader to acquire both common and private information. In this set-up, we have shown that, under some fairly mild conditions, there exists an optimal incentive policy for the leader, which is affine in the dynamic information and generally nonlinear in the static (common and private) information.

As a part of this project, we have also investigated the applicability of the feedback Stackelberg solution concept (developed primarily for discrete-time problems) in continuous-time Stackelberg differential games, and have reported some preliminary results in [17.51]. More extensive results regarding this problem will be reported in the next period.

17.3 Control Strategies for Complex Systems for Use in Aerospace Avionics*

Whenever model uncertainty is present or a range of operating conditions is anticipated, engineering analysis and design must deal with questions of sensitivity. Performances of manufactured components are necessarily specified with nonzero tolerances. The parameter values which characterize these components are therefore uncertain. These parameter values may change during the operating lifetimes of the components due to aging and due to changes in environmental conditions, such as pressure and temperature. In addition, mathematical models used for analysis and design of actual systems cannot possibly lead to predicted performance which exactly matches the performance of the actual systems. It is useful to regard some of the

* This work was supported by the U.S. Air Force under grant AFOSR-78-3633.

parameters of the models as uncertain in order to make these models more realistic. The combined effects of parameter uncertainties on overall system behavior are of principal consideration in any system design.

Our objective here has been to advance the current state of knowledge under both cooperative and noncooperative solution concepts. In [17.2], several new results have been reported concerning stochastic team problems with general partially nested information patterns and also the Nash equilibrium solutions of stochastic nonzero-sum dynamic games with quasi-classical information patterns. Recently, we have developed an equilibrium theory for a more general class of multi-person multi-criteria stochastic decision problems wherein the decision makers have different subjective probability measures on the uncertain quantities [17.47], i.e., for problems which do not admit a common underlying probability space. For such decision problems, we have introduced the concepts of locally and globally stable equilibrium solutions, and have studied the existence and uniqueness of such equilibria under certain conditions on the loss functionals and the subjective probability measures. Certain explicit results and analytic solutions have also been obtained and reported in [17.47].

On another topic, an important outgrowth of the singular perturbation methodology has been the analysis of adaptive systems with reduced order models [17.58,17.19,17.18,17.36,17.20, and others]. The error in model order is due to the presence of fast unmodeled parameters. A "dominant richness" condition has been introduced under which adaptive identities and observers can be made robust with respect to parametries. To extend this methodology to the case of feedback adaptive control the robustness of hyperstability properties has been analyzed.

Finally, as an application of chained aggregation, a study of "near" unobservability has been made [17.70]. This concept has been developed geometrically in terms of the canonical angles between an observable subspace L and an A-invariant subspace V. The role of eigenvalue separation in this problem has been clarified, leading to a contact with singular perturbation theory.

17.4 Large Scale Systems*

We highlight two classes of recent accomplishments on games. One class of results pertains to the well-posedness of singularly perturbed games [17.34]. For practical reasons it is desirable to employ reduced order models for the determination of game strategies. We have demonstrated that the natural singular perturbation approach leads to ill-posed solutions but we also demonstrated how to obtain well-posed reduced order models. The key to the successful development of such reduced order models is the preservation of the information structure.

A second class of our results we wish to highlight is the use of incentives to achieve global team optimality for the leader [17.37,17.2]. Basically, the idea is for the leader to apply a strategy which induces the followers to optimize the leader's objective while optimizing their own.

Another significant accomplishment is the two time scale methodology [17.22,17.59,17.69,17.55] for modeling of large scale dynamic networks such as power systems and Markov chains. A fundamental relationship between weak coupling and time scales has been revealed and used for systematic determination of coherent areas as local fast subsystems and their interactive core, as the slow aggregate subsystem. This type of modeling naturally leads to a scheme for fast decentralized and slow coordinated control, which has been developed for Markov chains and queueing networks.

Finally, a detailed geometric analysis of chained aggregation has been made [17.25]. This has led to a general version of three-control-component design, a hierarchical control strategy for large scale systems. This approach exploits the a priori information structuring present in the system and system output measurements. Connections with reduced order modeling, especially the role of residual feedback, have been examined.

* This work was supported by the National Science Foundation under grant ECS 79-19396.

17.5 Power System Normal and Security State Assessment*

Results have been obtained in the two areas of voltage collapse and maximum system loadability. As a variable allocation problem, voltage collapse has been found to be directly related to generator excitation and transformer tap limits. The normal control algorithm for dispatching transformer taps during contingencies can result in extreme demands for reactive power from sources with finite reserves. Alternative approaches to voltage control are currently being considered to minimize the possibility of voltage collapse.

Direct transient stability methods are being integrated with conventional maximum system loadability methods to replace exhaustive time domain simulations. The "first cut" fast transient stability calculation was developed to allow the dynamic constraint to be enforced in the contingency evaluations required for the maximum loadability calculation. The method employs an approximate Potential Energy Boundary Surface (PEBS) approach together with linear load flow algorithms.

17.6 Power System Reduced Order Modeling*

The traditional models used to analyze large scale power systems contain many inconsistencies resulting from heuristic order reduction and model simplification. Several of these models have been successfully derived from a singular perturbation approach while others have been shown to be void of mathematical justification. In each case, improved models can be obtained through higher order corrections to the singularly perturbed model. Work is continuing to develop a consistent set of reduced order models for all of the components and interconnections in a large scale power system.

---

* This work was supported by industrial funding through the University of Illinois Power Affiliates Program 81-82.

References

[R1] E. N. Lorenz, "Deterministic non-periodic flow," J. of Atmospheric Science, vol. 20, pp. 30-141, 1963.

[R2] See Synergetics, (H. Haken, Ed.), Springer-Verlag, New York/Berlin, 1977. Various papers refer to Veda's work.

[R3] C. T. Sparrow, "Chaos in a three-dimensional single loop feedback system with a piecewise linear feedback function," J. of Mathematical Analysis and Applications, vol. 83, pp. 275-291, 1981.

[R4] S. A. Orszag and J. B. McLaughlin, "Evidence that random behavior is generic for nonlinear differential equations," in Physica 1 D Nonlinear Phenomena, pp. 68-79, North-Holland Publishing Co., 1980.

18. DIGITAL SIGNAL AND IMAGE PROCESSING

Faculty and Senior Staff

E. I. El Masry
T. S. Huang
W. K. Jenkins
D. C. Munson, Jr.
J. L. C. Sanz

Graduate Students

E. J. Altman
A. C. Bovik
A. J. Brown
M. Desai
H. Fan
T. Fu
D. A. Hayner
W. E. Higgins
W. F. Kappauf
E. C. Martin
J. D. O'Brien
D. F. Paul
D. G. Payne
R. C. Rose
A. C. Segal
J. H. Strickland, Jr.
R. Y. Tsai

18.1 New Directions in Multidimensional Signal Processing*

This research project spans the areas of multisensor array processing, linear space varying processing, and nonlinear processing using order statistics. In array processing we have developed a unified treatment of spotlight mode synthetic aperture radar (SAR) and computer-aided tomography (CAT). We have shown that Fourier domain reconstruction, based on the projection-slice theorem from CAT, is also the underlying principle in spotlight mode SAR. In particular, the signal recorded at each SAR transmission point is approximately the Fourier transform of a central projection of the imaged ground area. A number of important issues involving resolution, sampling rates, waveform curvature, the Doppler effect, and motion compensation have been examined within the context of this new SAR interpretation. In addition, we have modified the convolution-back-projection algorithm from CAT, and applied it to the SAR problem. Preliminary indications are that this algorithm provides higher resolution than current

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

methods of SAR processing.

Work is also underway on the subject of digital beamforming for sonar. In a practical situation, the number of sonar sensors may be restricted by economic or physical constraints. This difficulty can be partially overcome by using signal extrapolation. We have applied a bandlimited extrapolation algorithm to this problem and characterized its performance both analytically and through computer simulation. For a sinusoidal signal it is possible to extrapolate to two or three times the length of the physical array. The beam performance is thus enhanced and is compatible with that obtained using many more sensors.

In the area of linear space varying processing we have derived the minimum permissible sampling rate for the digital implementation of an analog shift variant system. The necessary rate is easily computed from parameters of the bi-frequency map of the desired analog response. Potential applications include digital restoration of images degraded by linear spatially varying operations.

We have made further progress in the area of nonlinear processing using order statistics. A generalized median filter has been studied whose output is a weighted sum of the input order statistics. An explicit formula has been derived for the optimal weight values in the order statistic filter (OSF), assuming white background noise. We have filtered several images plus noise with a linear averager, a median filter, and the optimal OSF for a constant background. We found that the OSF provides a compromise between the smoothing properties of the linear filter and the edge sharpness offered by a median filter. Further generalizations of the median filter are currently being investigated.

18.2 Support-Limited Signal and Image Extrapolation*

One of the most important and difficult questions in signal and image processing is: How can we reconstruct signals and images from incomplete data (observations)? We have embarked on a basic research project to study a particular problem in this area, that of support-limited extrapolation. In

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

the one-dimensional form, the problem is the following: Given the Fourier transform F(u) of a function f(t) in a finite interval, determine f(t) under the assumption that f(t) is of compact support. In the mid and late 1970's two efficient algorithms (Gerchberg-Papoulis, Cadzow-Sabri-Steenart) were proposed, which looked very promising. However, up to now no successful applications of these algorithms to real-world problems have been made. We think the reasons are twofold.

(1) No one has studied the effects of discretization of these algorithms.

(2) No one has modified these algorithms or come up with new algorithms which take account of the noise in the observed data in an effective way.

We have been concentrating our effort on these two aspects. Some preliminary results have already been obtained. In particular, we have generalized Cadzow's algorithm, and shown that the solutions from the discrete algorithm converge to the solution from the continuous algorithm under certain rather weak conditions.

18.3 Low-Noise Digital Filter Structures*

Error spectrum shaping (ESS) is a technique that uses quantizer feedback to reduce roundoff noise and limit cycle amplitudes in digital filters. Nearly all past work on ESS has dealt with second-order filters. In our recent work we have shown how to choose the ESS coefficients optimally for high order filters composed of cascaded second-order sections. We have compared the noise gains of optimal and suboptimal ESS structures, and the section-optimal structure derived using the Mullis and Roberts state-space approach; the ESS structures performed well in comparison. In addition, a heuristic strategy for ordering the second-order sections has been developed based on the ideas underlying ESS. This strategy further reduces roundoff noise, especially for elliptic filters.

We have also applied ESS, in a much different role, for the design of short wordlength FIR filters. Instead of rounding infinite precision filter coefficients, we have used an ESS quantizer to distribute the error due to

---

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under Grant N00014-79-C-0424.

rounding nonuniformly throughout the frequency band. As an example, for cases in which the stopband response must be very low, the ESS technique can effectively place into the passband nearly all of the error due to coefficient rounding. We are presently concentrating on several factors involved in the design of the ESS feedback filter.

18.4 Design of IIR Digital Filters Using Multiple Criterion Optimization*

We are conducting an investigation of the applicability of the concepts and algorithms of multiple criterion optimization (MCO) to the problem of optimally trading off magnitude and phase response in IIR digital filter design. Particular attention is being paid to the formulation of the simultaneous magnitude and phase design problem. Results to date are extremely encouraging. As compared with an elliptic design, the MCO approach can produce filters having magnitude responses that are virtually as good and phase responses that are much more linear.

18.5 Number Theoretic Concepts for the Realization of Failure Resistant Signal Processors in VLSI Circuit Technology**

This research involves the study of number theoretic concepts which can improve speed, reduce hardware complexity, and provide self-checking performance in specialized digital processors such as digital filters or FFT processors. In particular, residue number system (RNS) concepts appear to provide many features that are required to integrate custom designed functions in VLSI circuits [R1,18.15,18.16].

Three significant results have been obtained that alleviate some of the practical difficulties in using RNS arithmetic in VLSI processors:

(1) the design of a high speed pipe-lined RNS error checker resulted from a mathematical study of the error location algorithm [R1],

---

* This work was supported by the National Science Foundation under Grant ECS 80-07075.

** This work was supported by the National Science Foundation under Grant ENG-79-01686.

(2) a new error location algorithm based on the concept of expanded projection was derived [R2], and

(3) an architecture for a standard computational element was developed for the VLSI realization of digital processors designed with modular arithmetic [R3].

Also, RNS product codes have been studied to determine if they offer more desirable properties for VLSI realization. A hardware architecture for an error checker based on an RNS product code has been designed [18.15]. Further studies will reveal how the special features of a product code can improve VLSI architectures for fault tolerant performance.

REFERENCES

[R1] S. D. Fouse, G. R. Nudd, G. M. Thorne-Booth, P. A. Nygaard and F. D. Gichard, "Image understanding of IU algorithms," Technical Report USCIPI 1010 (Chapter 2), Hughes Research Laboratory, Malibu, CA, 1982.

[R2] W. K. Jenkins, "The design of error checkers for self-checking residue number arithmetic," submitted to the IEEE Trans. on Computers for a Special Issue on Computer Arithmetic, to appear in March 1983.

[R3] W. K. Jenkins, "A standard computational element for the VLSI realization of digital processors using modular arithmetic," Proc. of the 16th Asilomar Conf. on Circuits, Systems, and Computers (Invited Paper), Nov. 1982, (to appear).

19. CLIMATE AND CROP STUDIES*

Faculty and Senior Staff

Paul Handler

Graduate Students

M. Welcome

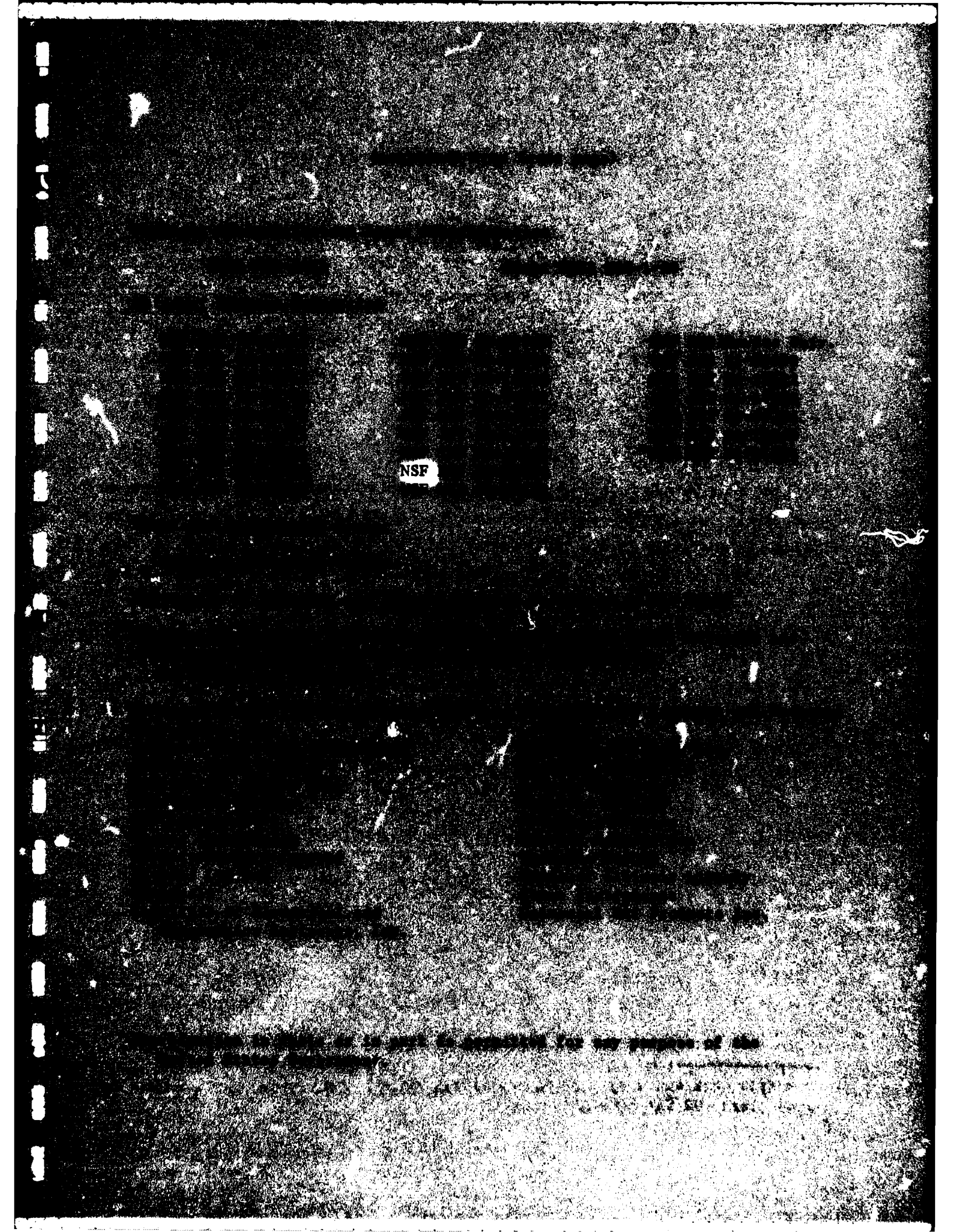
David LaMar

An ongoing study is continuing to relate climate anomalies in one part of the world at a prior time to crop growing conditions in other regions of the world at some later times. A number of interesting climate-crop patterns have been found which have a high probability of repeating themselves every 3-7 years.

The climate-crop patterns can also be used as a means of crop forecasting. Various types of time series analysis have been developed for recognition of these climate-crop patterns. Some of the crop time series contain data starting in 1866. A paper describing the relationship of crops in Australia and Indonesia to climate anomalies in the eastern tropical Pacific Ocean has been submitted for publication.

---

* This work was supported by the United States Department of Agriculture under grant AGR SEA 58-519B-0884.


NSF